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One-day Conference on:

Power Supply, EMC and Signalling, In Railway Systems

Tackling Power Quality problems in Railway Systems

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IEEE (HK) PES/IAS/PELS/IES Joint Chapter

I

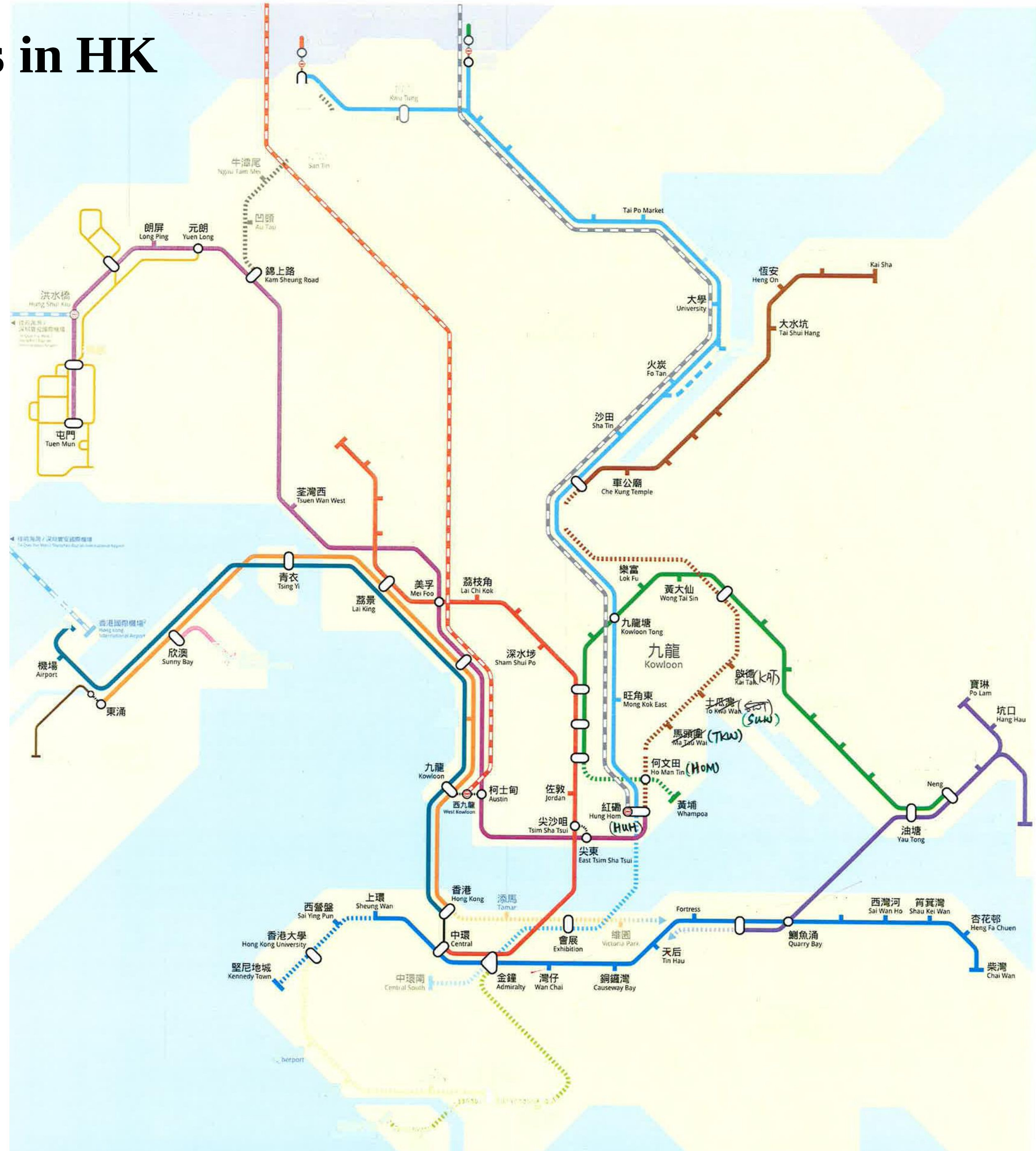
Mass Transit systems in HK

In HK, there are 4 major mass transit systems of different power supply sources:

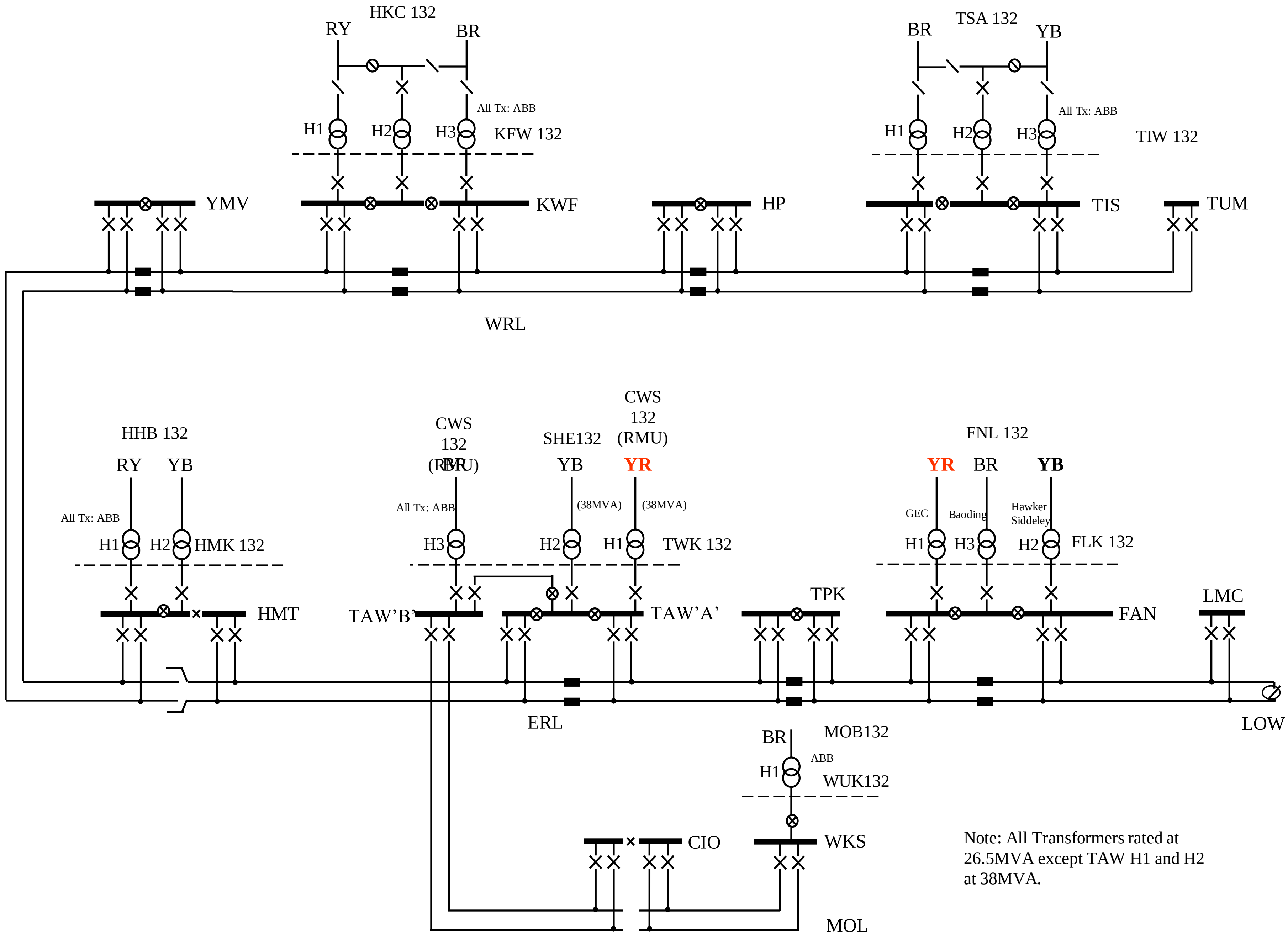
1. 25kV ac 1-phase (KCR)
2. 1.5kV dc (MTR)
3. 750V dc (LRT)
4. 600V dc 3-ph (APM)

All these systems are operated under MTRCL

(For clarity, KCR, MTR, LRT and APM here are merely used to distinguish the different types of electrified mass transit systems in HK)

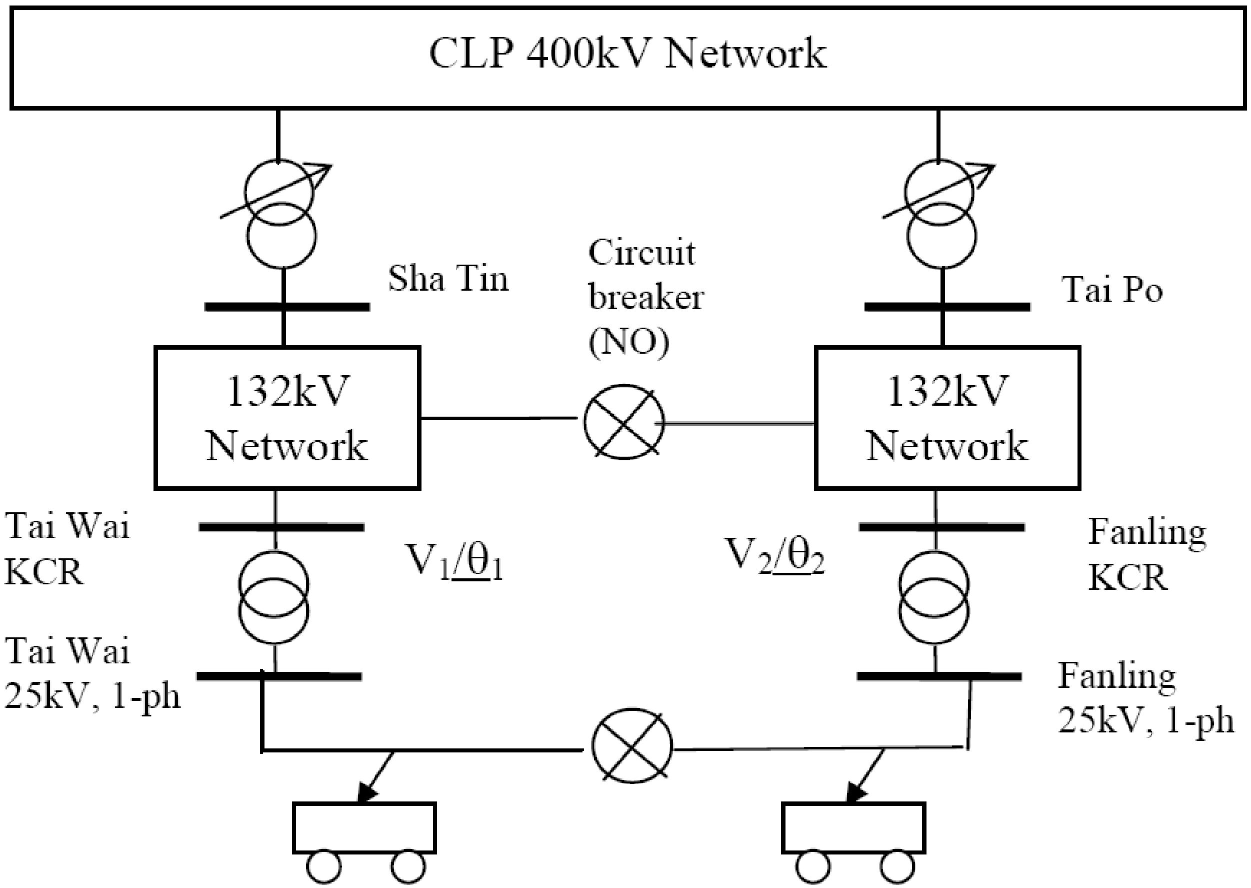


25kV TRACTION POWER SYSTEM (2009)



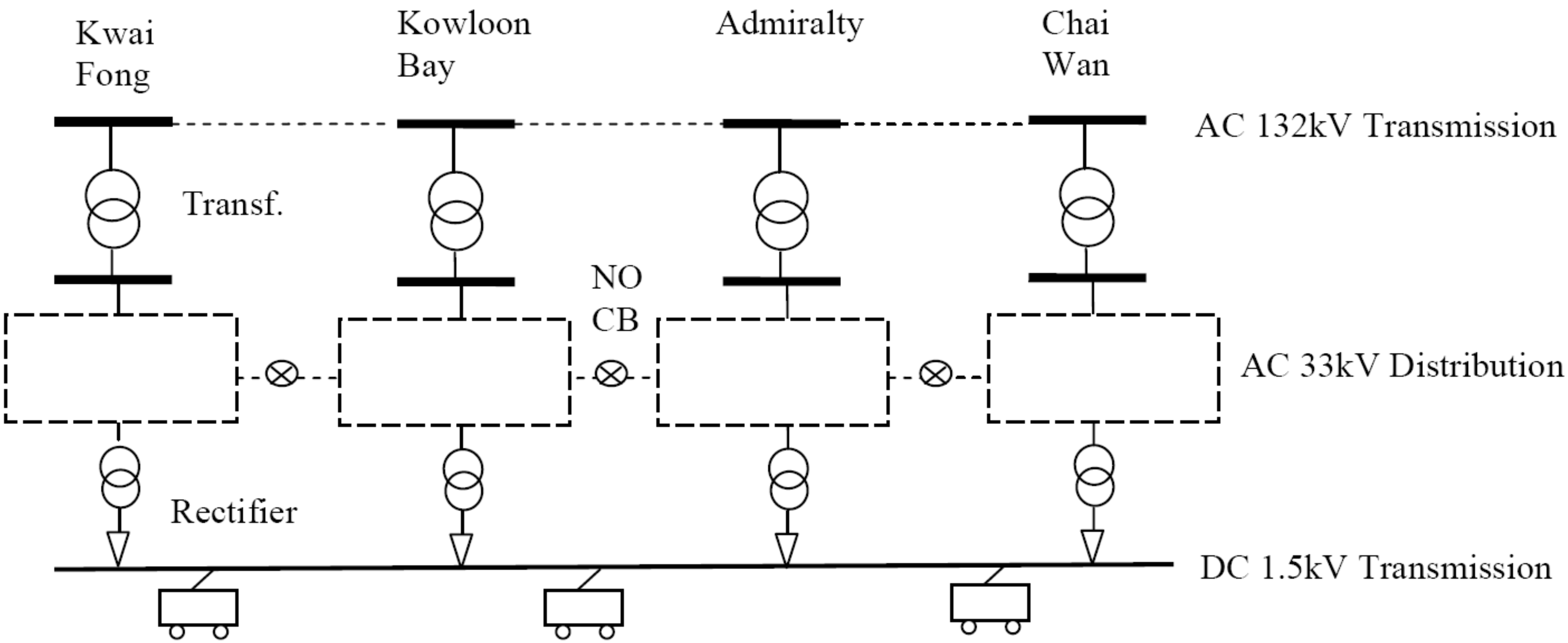
Note: All Transformers rated at 26.5MVA except TAW H1 and H2 at 38MVA.

Supply to East Rail Line in KCR system in 90's



- Only one 132/25 Tx feeds each section, and failure of any 132/25kV Tx will lead to supply loss to trains

Supply to MTR 1.5kV traction in 90's



- The 1.5kV dc system is feed by multi rectifier Tx in parallel.
- Failure of any rect Tx, or even 132/33 kV Tx will not lead to supply loss of trains, i.e. power supply much more reliable

Electrification of Traction System

Advantages

- Larger acceleration/retardation & maximum speed, hence schedule speed
- Higher power to weight ratio of motive power
- Higher torque, hence larger carrying capacity
- More traffic density, because of the above
- More flexibility because of multiple unit operation
- Low maintenance and running cost
- Shorter maintenance/repairing time
- Environmental: quiet, and without smoke, corrosive fume and coal dust
- Comfort: less vibration due to rotatory torque
- Regenerative braking possible: quick, reduce wear, and energy feedback

Disadvantages

- High capital cost
- Failure with electric supply
- Increased clearances required for overbridges and tunnels
- Affecting the use of cranes
- Electrical safety hazard
- Interference
- Dirty load: voltage fluctuation, harmonics, unbalance

Environmental Consideration

- Less energy per passenger kilometre than cars
  - reduced use of non-renewable fossil fuels
  - reduced emission of green house gases
- - no air pollution
- - more quiet

Relative merits of DC system

- Train equipment: lighter, more efficient and less costly
- Lower energy consumption
- Conductor-rail distribution less costly than OHL
- Less interference problem
- Regenerative braking: more efficient, less complication
- Facilitate multi source infeeds, more reliable supply

Relative merits of AC system

- higher line voltage:
smaller current $\Rightarrow$ less I^2R loss and less pu voltage dip ΔV
($\Delta V = XI = XS/V$ kV and $\Delta V_{pu} = \Delta V/V = XS/V^2$, where S=MVA)
- fewer infeed substations (but only one source per zone)
- more suitable for long distance service
- Minimum Stray current effect

Merit of DC Traction System

In MTR dc system, all the 1.5kV rectifier outputs can be coupled and every train will be supplied by multi rectifier sources.

In case of one or several Tx failure, the train service is not disturbed.

Choice of AC and DC systems

In terms of voltage dip, ac system is preferred, since it allows 30% voltage dip and hence fewer feeding substations, suitable for long distance intercity trains

In terms of supply security, dc system is much better. Suitable for urban line, which allows more feeding stations

Supply Rule from CLPP Website

Type of Distortion	Type of Abnormal Load	Operational Limit
Voltage	Electric arc furnace	• for 132kV and below 2 %
Fluctuation	Motor starting	• Infrequent (intervals exceeding 2 hours) 3 % • Frequent (intervals not exceeding 2 hours) 1 %
	Rolling mill and traction (motor starting intervals not exceeding several minutes)	• Step-type change : up to 66kV 1 % 132kV ¾ % • Ramp-type change : up to 66kV 1 % /sec 132kV ¾ % /sec • Limit of total change : up to 66kV 3 % 132kV 2¼ %
Voltage Unbalance	Single phase electric traction load	• Voltage : negative sequence 2 % of positive sequence • Current into generators : negative sequences 5 % of positive sequence

(Supply rule 2000 from CLP website)

Harmonic Voltage Distortion	Electric arc furnace	• At 132kV or above odd harmonic distortion 1 % total harmonic distortion 1½ % • At 66kV or 33kV odd harmonic distortion 2 % total harmonic distortion 3 % • At 11kV odd harmonic distortion 3 % total harmonic distortion 4 %
Harmonic Current Distortion	Other Non-linear Equipment with size 'I' in Ampere	• At 380V/220V total odd harmonic distortion: I < 30A 20 % 30A ≤ I < 300A 15 % 300A ≤ I < 600A 12 % 600A ≤ I < 1500A 8 % I ≥ 1500A 5 % total even harmonic distortion: 25 % of the odd harmonic limits

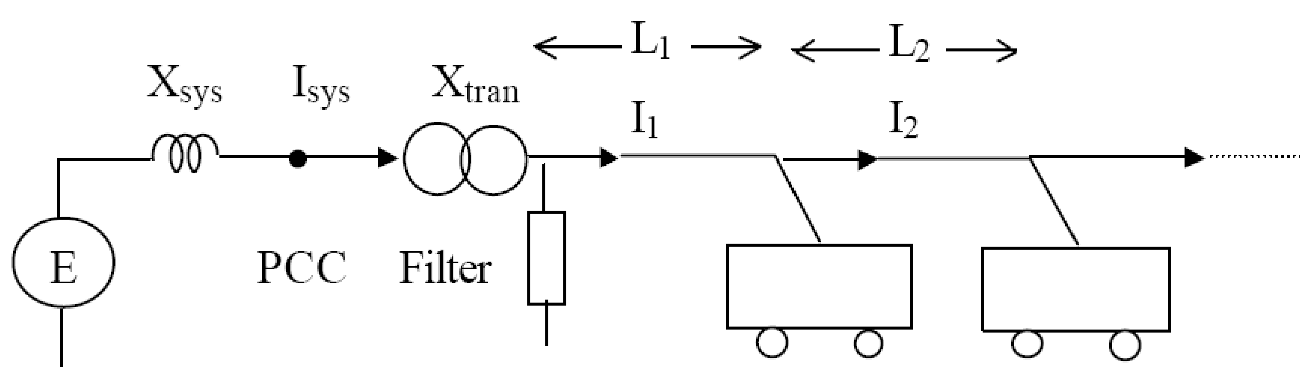
Supply system voltage 'Pollution' due to ac traction

AC Traction is the only consumer that contributes all of the above 'abnormalities' and at least three pollutions are associated with voltage. Because of the momentary (on & off) nature, and with frequent change of operation mode, sharp voltage change in traction system is inevitable, which needs to distinguish here the two common terms with voltage:

1. Voltage regulation is to determine the minimum voltage for the traction drive system (The allowable limit of 25kV is 17.5kV, i.e. allow 30% voltage dip). The voltage dip ΔV_n (at the n^{th} train) is due to heavy train current and the system impedance, given by

$$\Delta V_n = I_{sys} (X_{sys} + X_{tran}) + \Sigma I_j L_j Z$$

where L is the distance in km and Z is line impedance per km.
Thus, the most remote train will experience the largest voltage dip.



2. Voltage fluctuation is the flickering ($\Delta V = I_{sys} X_{sys}$) experienced by other consumers at the point of common coupling (PCC) caused by the frequent train on/off and load changes, e.g. the 10Hz flicker is most unpleasant to human eye.

Whilst the voltage regulation will affect the train operation, the voltage fluctuation will affect the 3-phase power system and the other consumers connected to the 132kV point of common coupling (PCC), and is the concern of supply utility.

Remedies for both

a) Install capacitive compensator/filter at strategic locations

b) Sectionalize the railway system

Impact of Harmonics due to AC & DC Traction Loads

Extracted from IEEE/HKIE seminar

Impact of Traction Harmonics to Power System, 2010 Nov14

(Supply rule 2000 from CLP website)

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Appears to have no harmonic current limits at 132kV

Traction Harmonics

Harmonic Source

AC & DC drives

Adverse Effect of Harmonics

Overheating of conductors

Overheating of electrical equipment

Mechanical oscillation of electrical machine

Telecommunication interference

Inaccurate meter readings

Disturbance to sensitive electronic equipment

False operation of protection equipment

Standards

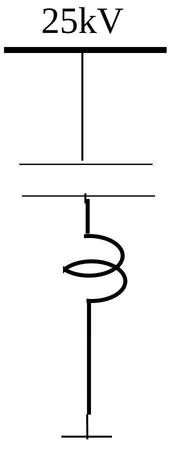
Engineering recommendation G5/3, G5/4

IEEE standard 519-1992

Harmonic current in electrified ac system

KCR electrification began in 80's but with very poor power factor.
Capacitors were installed in Tai Wai 25kV for pf improvement

In the early stage, train drives were of tap-changer type, and 3rd harmonic (h=3) dominant.
The installed cap bank was then modified to add series reactor to become third harmonic filter.



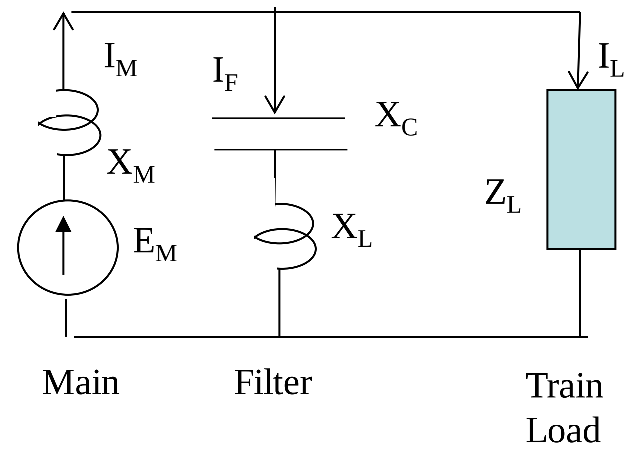
Harmonic increased with the introduction of thyristor type drive.
With the advances of power electronics, the speed and traction force of new drives are much enhanced but the harmonics are much increased.

<u>Dual functions of 3rd harmonic passive filter in East Rail</u>
It provides capacitive compensation at 50Hz and also absorbs harmonics of $h \geq 3$.

System representation at fundamental frequency

Main supply (50Hz) is represented by Thevenin equivalent (E_M & X_M).
Load represented by impedance $\mathbf{Z}_L$
The shunt filter (connecting in parallel with load) provides capacitive compensation.

(In ac traction, X_M includes transformer X_T and system X_{SYS} and usually $X_T >> X_{SYS}$)

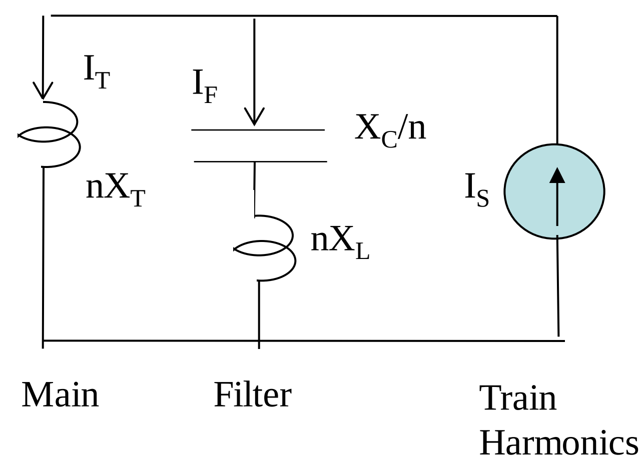


System representation at frequency 50n (Hz)

Main is represented by single inductance nX_T without emf, since it is a 50Hz source only.

The harmonic produced by the train is often represented by Norton ($\mathbf{I}_S$ and $\mathbf{Y}_S$), and very occasionally by Thevenin ($\mathbf{V}_S$ and $\mathbf{Z}_S$).

Since $\mathbf{Y}_S$ is a very complicated function, $\mathbf{Y}_S$=0 is usually assumed (most pessimistic assumption for Norton).



(In subsequent harmonic diagrams, n may be skipped for simplicty.)

Harmonic current sharing between Transformer and Filter (at 25kV)

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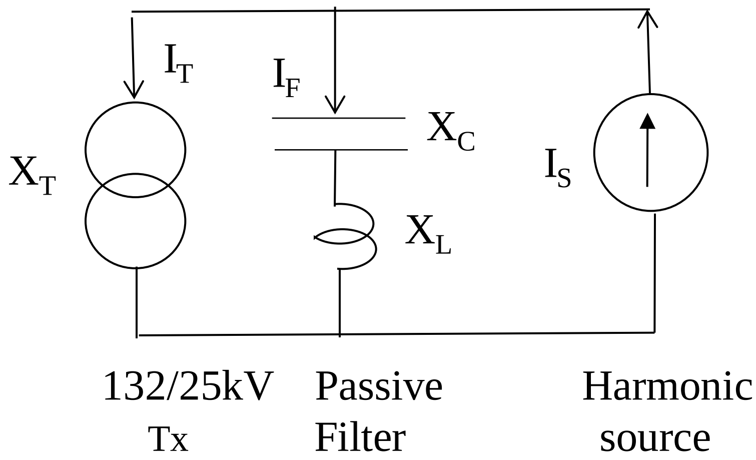

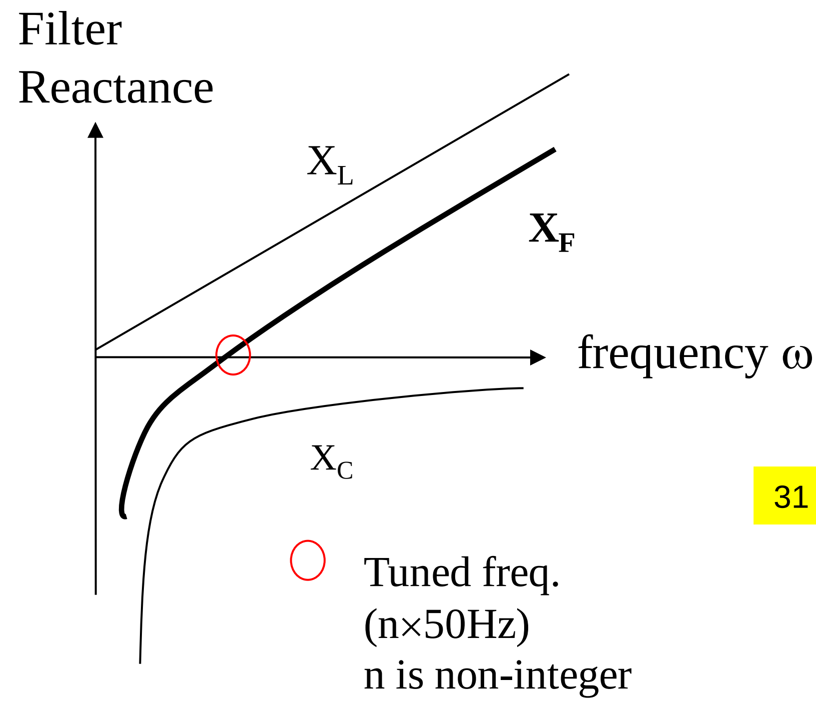

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Filter reactance

$$X_F = X_L + X_C = \omega L + (-1/\omega C)$$

I_S shared between X_T and X_F

13 $I_T = I_S\, X_F / (X_T + X_F)$

12 $I_F = I_S\, X_T / (X_T + X_F)$

The tuned (resonant) freq. must be less than the targeted harmonic freq. (i.e. n<h)

The smaller X_F, the less I_T flow to the PCC, and the larger I_F (filter more harmonic absorption)

Harmonic current with Filter tuned at 2.5x50=125Hz

pu on 25kV & 26.5MVA base and assumes 4MVA capacitive compensation 12

X_L=**29.76**×26.5/25^2=1.26pu, X_C=**-186.01**×26.5/25^2=-7.89pu. (Given: X_T=0.18pu)

				Harmonic number n					
			50Hz	2	3	4	5	6	7
Reactance (pu)	Indcutor	X_L	1.26	2.52	3.79	5.05	6.31	7.57	8.83
	Capacitor	X_C	-7.89	-3.94	-2.63	-1.97	-1.58	-1.31	-1.13
	Filter X_F	X_L+X_C	-6.63	-1.42	**1.16**	3.08	4.73	6.26	7.71
	Tx.	X_T	0.18	0.36	0.54	0.72	0.90	1.08	1.26
Harmonic Current (%)	Filter	I_F		-33.97	31.83	18.97	15.98	14.72	14.05
	Tx.	I_T		133.97	68.17	81.03	84.02	85.28	85.95
	Source I_S	I_F+I_T		100.00	100.00	100.00	100.00	100.00	100.00

11 19 11

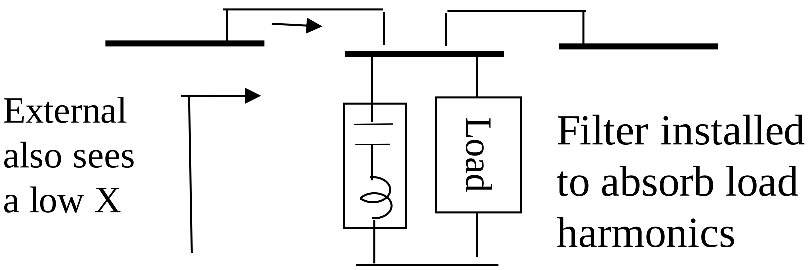
At n=3, X_F=**1.16** (positive) and the filter absorbs 32% I_3

At higher n, $X_F=nX_L+X_C/n$ is also positive, and it absorbs 16% I_5, 14% I_7 , ….

But at low n=2, X_F=-1.42pu, I_F absorbs -34%, i.e. I_T is amplified by 34% at Tx

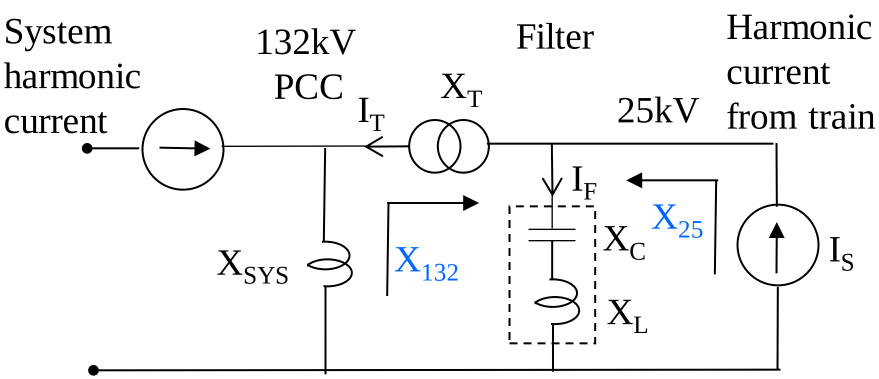
Fortunately, I_2 is very small in ac traction, 34% amplification is of no problem. 14

‘Problems’ of 3rd harmonic filter design in East Rail



Power system is rich in 3rd harmonics but the magnitude is unknown.

Possibly with fear of ‘resonance’, early filters in KCR tuned **not** closed to 150Hz had restricted the absorbing capacity of passive filter (32%) 13



For all frequency ranges: $X_T >> X_{SYS}$, $X_F = X_L + X_C$

$X_{25} = (X_T + X_{SYS}) // X_F \approx X_T // X_F$, $X_{132} = X_T + X_F$

Usually, I_{PCC} mainly flows via X_{SYS}, except when X_{132} is very small, i.e. at 132kV series resonance.

Resonance may be due to very low X_{25} or X_{132}, overloading the filter.

25kV series resonance: $-X_L = X_C$, or $X_F = X_L + X_C = 0$, i.e. when $X_{25} \to 0$

132kV series resonance: $-X_F = X_T$, or $X_T + X_F = 0$, i.e. when $X_{132} \to 0$

If the 3rd harmonic filter is tuned closed to 150Hz, say at 145Hz,

At 150Hz, $X_T = 0.54$ and $X_F = 0.18$ are both positive. 14

X_{25} ($\approx X_T // X_F \approx X_F$) is small, series ‘resonant’ design to increase absorption to 75%. 21

But this resonance is controllable since max $I_F \approx I_S$ and I_S (as well as X_F) are known, from which the filter rating can be properly determined without overcurrent nor overvoltage. 40

X_{132} ($\approx X_T + X_F \approx X_T$) is large and positive, irrespective of X_F value (small or very small). 13

150Hz series resonance at 132kV due to 3rd harmonic filter is impossible. 20

‘Resonance’ at frequencies other than 150Hz

Above 150Hz, both X_T & X_F are more positive, resulting in both $X_{132} \approx X_T+X_F$ & $X_{25} \approx X_T//X_F$ are more positive. 19

High frequency resonance due to 3rd harmonic filter is impossible.

At 50Hz, X_T=0.18pu. 132kV series resonance occurs if $X_{132}= X_T+X_F = 0$, 14
or if $X_F \approx$-0.18pu, i.e. if capacitive compensation is 26.5/0.18=147MVAr

At 100Hz, 25kV parallel resonance occurs if the capacitive compensation is 22MVAr

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But the maximum capacitive compensation in KCRC is only 4MVAr.

Conclusion :

Resonance (series or parallel) due to 145Hz filter is impossible.

Heavy 3rd harmonics in East Rail can be combated by tuning filter closed to 150Hz, with adequate filter rating.

Remark: X_{SYS} is the Thevenin reactance at PCC, including 132kV network & fault level.
If X_{SYS} is small, then $X_{25}=(X_T+X_{SYS})//X_F \approx X_T//X_F = X_TX_F/(X_T+X_F)= X_TX_F/X_{132}$.
At 132kV series resonance (a), $X_{132}\to 0$ implies $X_{25}\to\infty$, or $B_{25}\to 0$, i.e. 25kV parallel resonance (b). But (a) is associated with 132kV I_{PCC} while (b) with 25kV I_S.
However, (b) with current amplification is more severe than (a).
Since X_{SYS} is also unknown, it is assumed small in the present presentation.) 21

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Harmonic Problems in West Rail

Characteristics of new drive of SP1900 (IKK) train

- Unity power factor
- Rich in low harmonics with some high-order harmonics
- Passive filter (capacitive at 50Hz must cause over-compensation and overvoltage) is inappropriate for installation. 49

In my consultancy study including IKK train in the East Rail (one IKK with 4 convention MLR), for a scenario of the only IKK train in powering mode:

- poor and negative power factor = -0.427,
- over-compensation by 3MVAr and **over-voltage** (V=1.073pu)

Other Problems:

High-order (over 50^{th}) harmonics generated by unity pf drives

Passive filter tuned at, say, n=50.5 must amplify harmonics h<n, and may lead to resonance at some lower h's.

Passive filter cannot be installed to the West Rail.

Possible solution: Active Filter directly connected to at 25kV ? 50

(Present G4/5 regulation only covers h<51.)

Standard for Harmonics

	Harmonic	2	3	4	5	6	7	8	9	10	11	12	13	THD
G5/3	Current (A)	5	4	3	4	2	3	1	1	1	3	1	3	
G5/4	Voltage (%)	1	2	0.8	2	0.5	2	0.4	1	0.4	1.5	0.2	1.5	5%

Total harmonic distortion (THD) on voltage

G5/3: $$V_T = \sqrt{\sum_{2}^{\infty} V_n^2} < 1.5\%$$

"sufficient to use values of up to 19"

G5/4: $$V_T = \sqrt{\sum_{2}^{50} V_n^2} < 5\%$$

n>50 is ignored in THD calculation

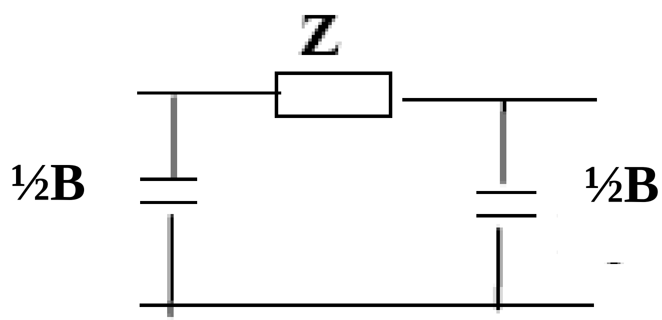
Necessity to revise existing regulation ?

High-order harmonics recorded beyond PCC

High order harmonic current were recorded at 132kV s/s beyond PCCs supplying West Rail and also East Rail.

These s/s are connected to PCC via 132kV cables.

A cable represented by π-equivalent has 3 parameters: R, L & C, where **Z**=R+jX, X=ωL and B=ωC at 50 Hz

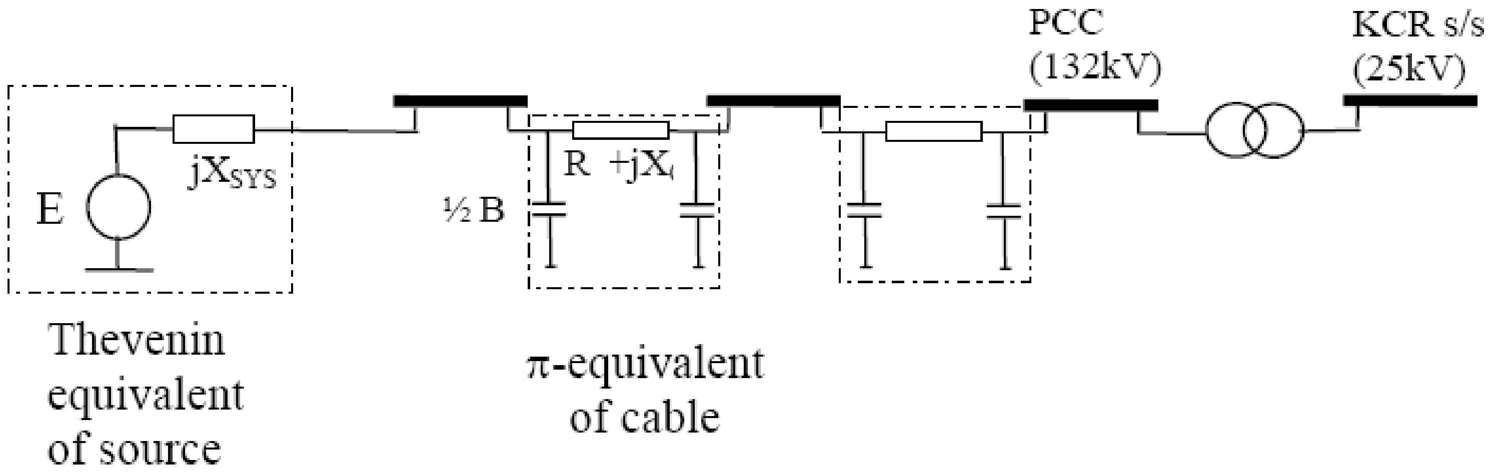


π equivalent of Cable

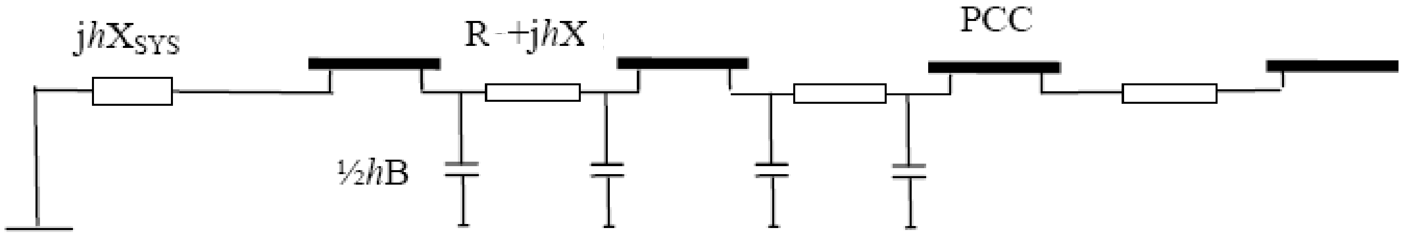
For h^{th} harmonic, $\mathbf{Z}_h \approx R + jhX$, and $B_h = hB$.
Both $\mathbf{Z_h}$ and B_h will increase with *h* and cable length.

The 50Hz charging current V^2B is very high at V=132kV.

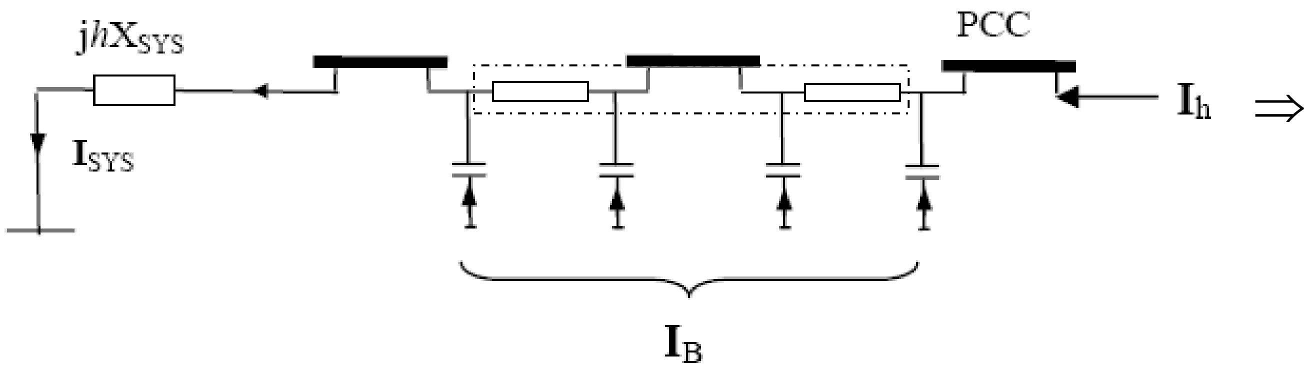
System modeling at 50Hz

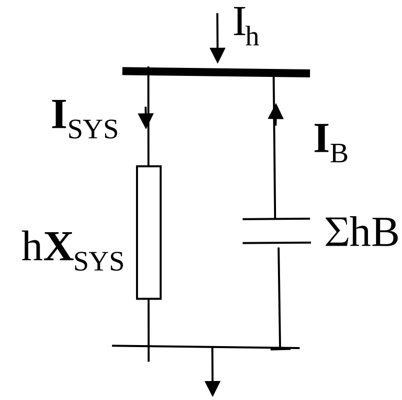


System modeling at h harmonic



Harmonic current flows at 132kV





Appro. equivalent circuit at s/s if $Z_h \approx 0$

I_h (small) from traction is injected to 132kV system via PCC, and will return via I_{sys} (positive) and I_B (negative)

I_{SYS} at a s/s is much amplified if $hX_{SYS} \approx 1/h\Sigma B$ (parallel resonance)

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To meet $hX_{SYS} \approx 1/h\Sigma B$, the location of resonance (ΣB), the harmonic order (h), and the time in a day (X_{SYS}) can vary.

Fortunately, many R's in the two Z branches and connected loads will attenuate current amplification in parallel resonance, if any.

Note the approximate equivalent circuit does not include 25kV (i.e. not related to filter design), and this 132kV resonance (parallel) may not be detected in KCR.

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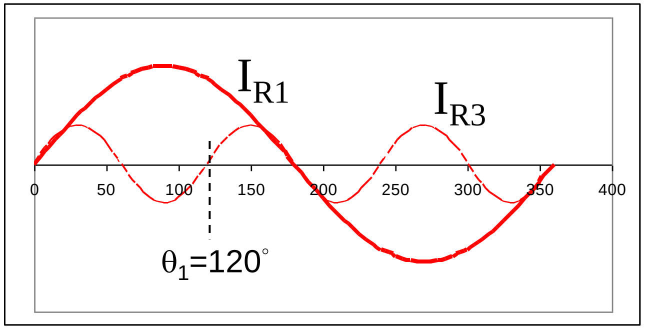
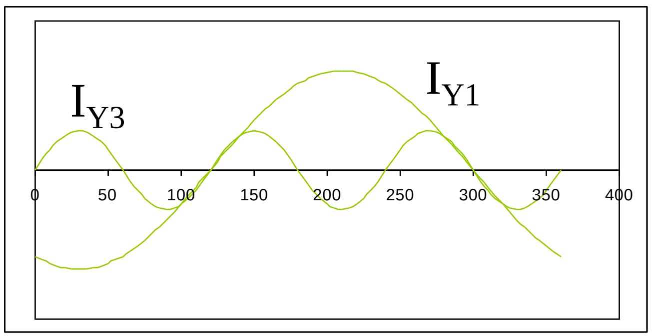
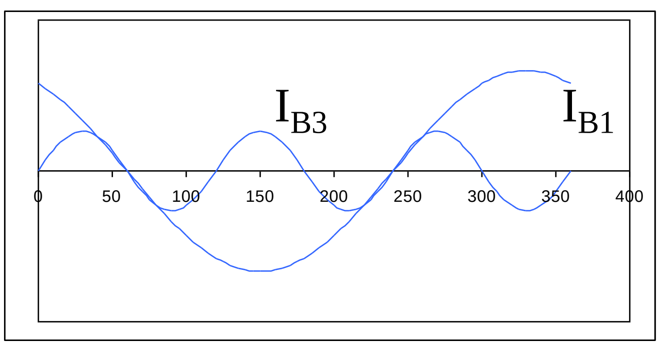
Effect of 3rd harmonic current in neutral wire for 3-phase

Harmonics in 3-ph system:







$\theta_1=\omega t$ for fundamental, $\theta_n=n\omega t$ for n^{th} harmonic

For the same time span t, $\theta_n=n\theta_1$

When 3th harmonics completes one cycle, the fundamental goes through only 120°

Under balanced load, the neural wire current

$I_N=I_R+I_Y+I_B=0$ for fundamental 50Hz

But, their 3^{rd} harmonics are in-phase

$I_{R3}=I_{Y3}=I_{B3}$ and $I_{N3}=3I_{R3}$

This also applies to harmonics of 6^{th}, 9^{th}, ….

If a system has, say, 40% 3^{rd} harmonic,

let $I_1=1$, $I_P=\sqrt{(1^2+0.4^2)}=1.077$, $I_N=3\times0.4=1.2$,

$I_N>I_P$ and the neutral wire may be overloaded.

I_3 (%)	0	10	20	30	40	50
I_P	1.000	1.005	1.020	1.044	1.077	1.118
I_N	0	0.3	0.6	0.9	1.2	1.5

Harmonic in Automated People Mover (APM) System for Airport
(initially installed with multi-leg filter)

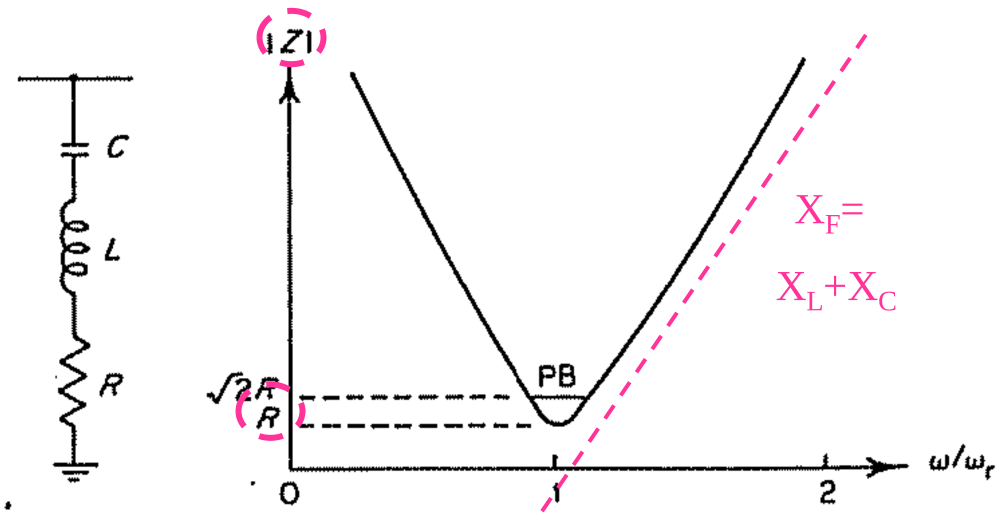
- The 3-ph 600V supply to APM does not have neutral wire, and I_3 is suppressed.
- Harmonics of 5, 7 &11 are rich and 3-leg filters were already installed.

- Whilst I_5 is absorbed by 5^{th} harmonic filter (<100%), it is amplified by 7^{th} harmonic filter.
- Similarly, 11^{th} harmonic filter must amplify I_5 and I_7. 16
- Resonance may occur at I_5 and I_7.

- Multi-leg filter may not be effective to absorb multi harmonics.
- A solution is to install only 5^{th} harmonic filter to absorb I_5, as well as I_7 and I_{11} (but with larger filter rating). 14
- Final solution : install active filter, since V is low (600V) 50

Traditional Concept on Singly tuned Filter

Why engineers do not aware lower harmonic amplification in mulit-leg filter?



The filter impedance is $\mathbf{Z}=R+j(\omega L-1/\omega C)$ and $|Z|=\sqrt{\{R^{2}+(\omega L-1/\omega C)^2\}}$ is always positive

At tuned frequency ω_r , $\omega_r L=1/\omega_r C$, and $|Z|=R$

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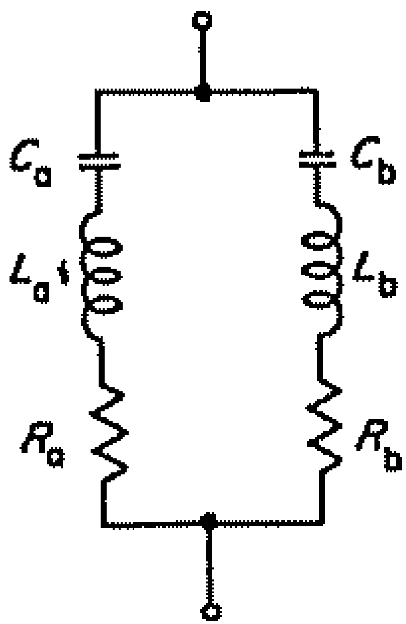
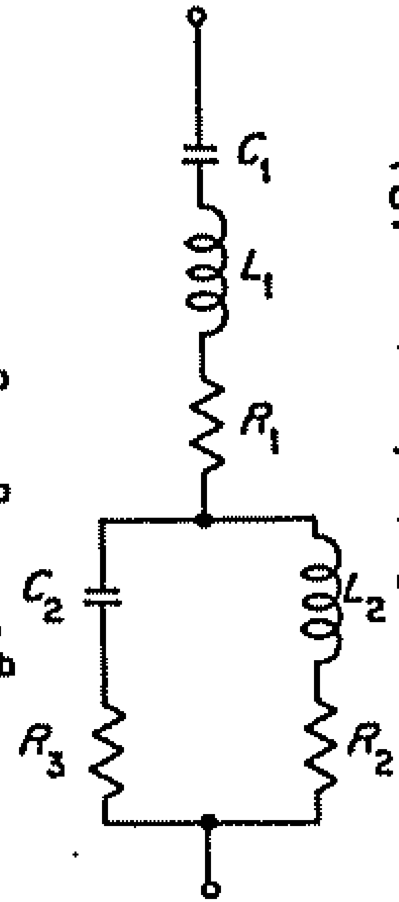
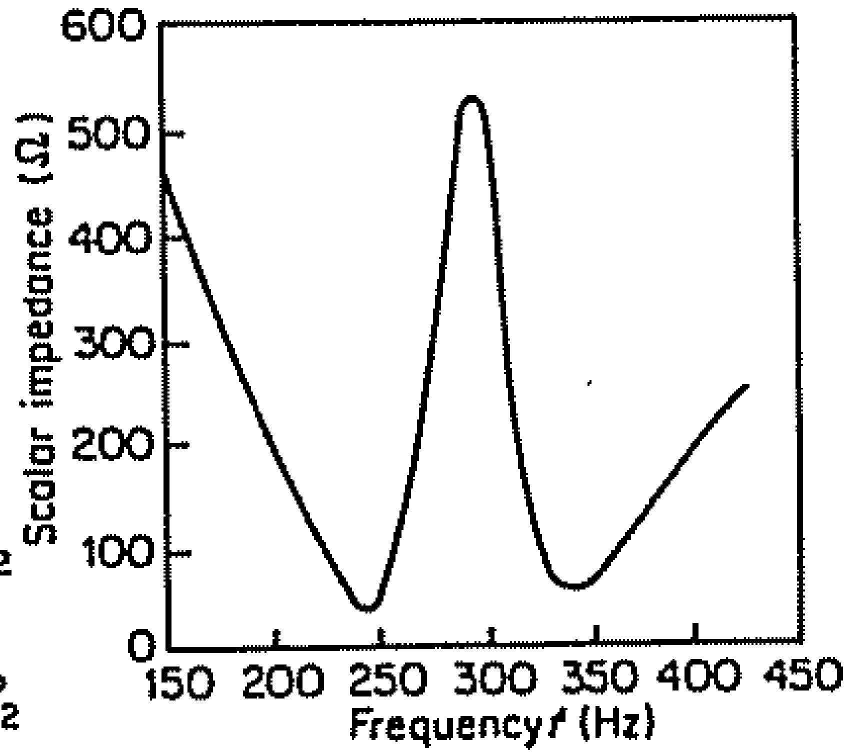
The filter has the lowest $|Z|=R$ (i.e. highest absorption) at $\omega_{r.}$ However, this tuning concept may be adequate to the filter design at power system, but inadequate at traction substation which has a 132/25kV Tx in parallel with the filter.

The absorption concept at $\omega>\omega_r$ also applies, but this concept has overlook that negative reactance X at $\omega<\omega_r$ will amplify the low-order harmonic flows in the Tx.

Traditional Concept on Double tuned Filter







Characteristic of a 2-leg filter
(5^{th} and 7^{th})

Similar inadequacy of using scalar impedance $|\mathbf{Z}|$ also occurs on double tuned filter, e.g. 2-leg filter.

Discrepancy of Traditional Concept

Filter impedance **Z**=R+jX is a complex number, a 2-D vector.

To fully depict **Z** variation with frequency f, a 3-D graphic is necessary. But 3-D analysis is complicated and difficult.

To depict **Z**-f relationship by 2-D, traditional concepts use 1-D of Z=|**Z**|, but the abrupt sign change of X is overlook. 29

In the present presentation, the small R is ignored and
Z≈jX is simplified to 1-D.
Finally the **Z**-f relationship becomes a 2-D problem. 11
The advantage is that the abrupt sign change of X and the harmonic current absorption/amplification can be estimated using simple excel program.

Another common error in filter design

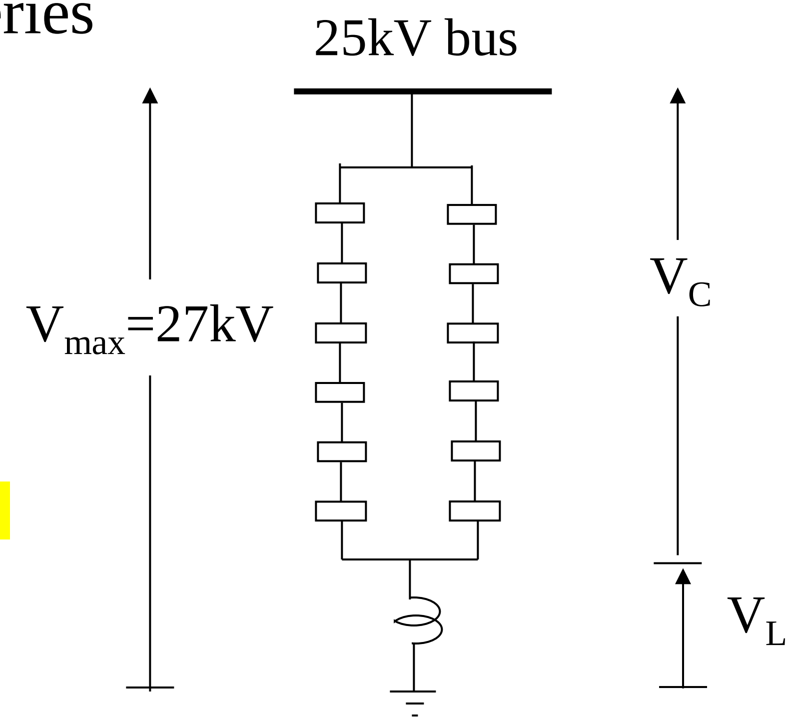
With passive filter, the 50Hz capacity compensation will be excess when less train at powering mode and may lead to over-compensation and over-voltage. The max. allowable voltage for KCR ac traction drive is 27.5kV. 12

Suppose each cap has a voltage rating of V_{cap}=4.5kV.
For V_{max}=27kV, the number of cap in series appears to be $s=V_{max}/V_{cap}=27/4.5=6$

However, the actual voltage across the cap is $V_C > V_{max}$ since V_C and V_L are of opposite sign 52

It should be $s=V_{max}/V_{cap}+X_L \omega C p$ 37

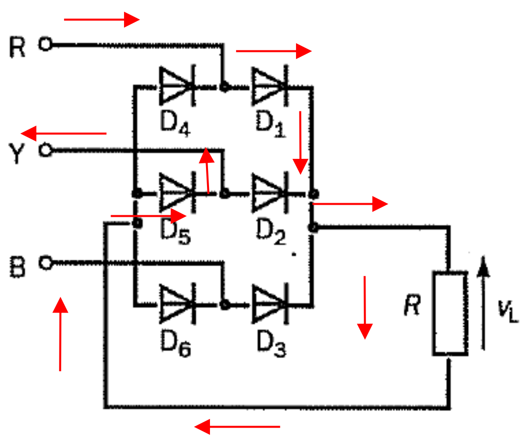
(Details to be provided in EE510)

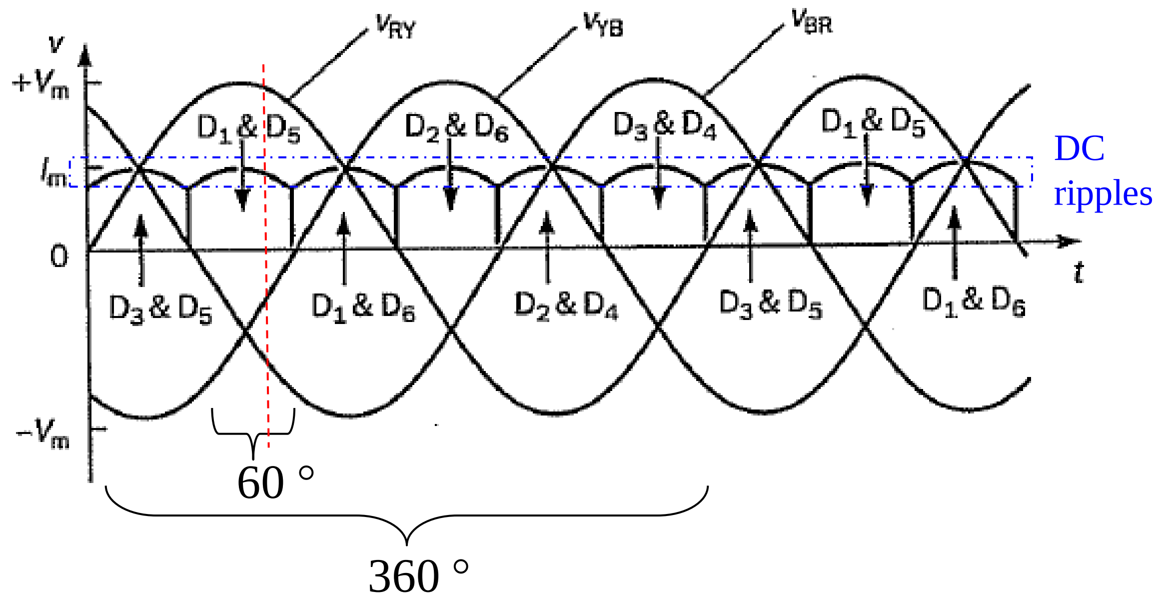


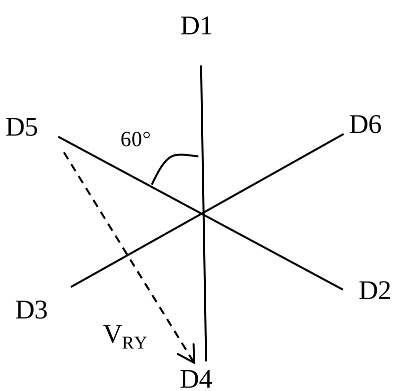
Filter design based on $s=V_{max}/V_{cap}$ may lead to capacitor insulation failure under higher voltage stress.

Harmonics in dc traction system

In 3-ph system, DC supply obtained from full wave rectifier is common.



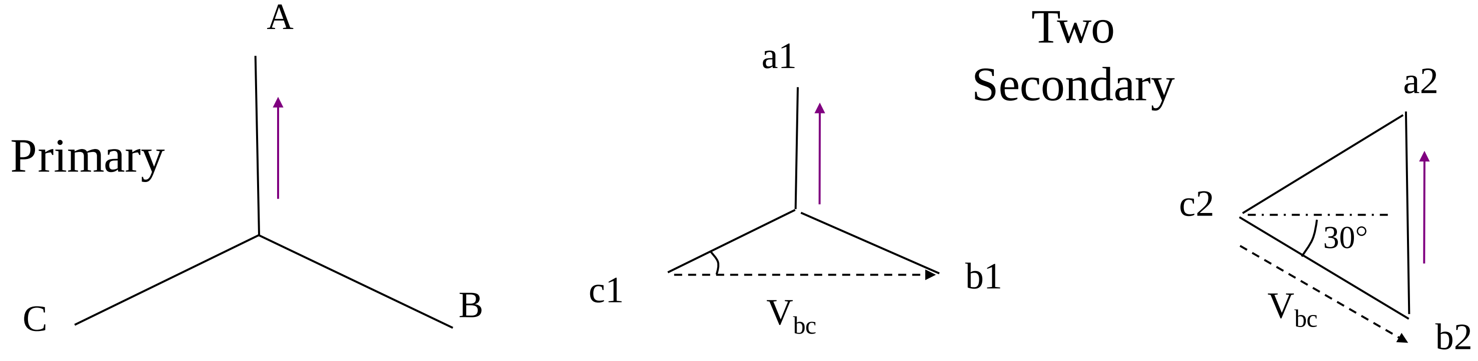




The DC output voltage has six 'sections' in one cycle (i.e. the so-called 6-pulse rectifier), and each section is of 360/6=60°.

DC ripple can be reduced by more pulse rectifiers

12-pulse Rectifier



If a 3-ph Tx has two sets of secondary windings of star and delta connections, the secondary line voltages will have an angle difference of 30°.

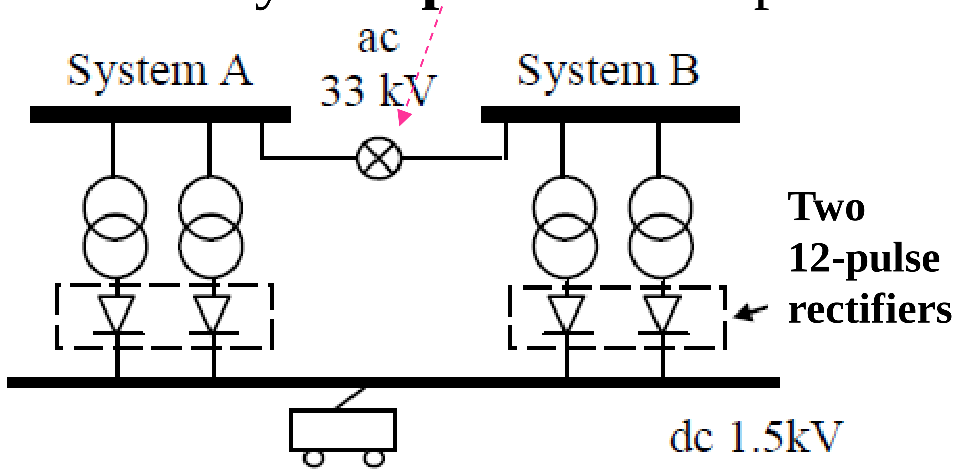
If a rectifier is fed by these two secondary windings, the rectifier output V_{DC} will be of 360/30=12 pulses, and the DC ripple is smaller than that of the 6-pulse rectifier.

For 12-pulse rectifier, harmonic current I_h with $h=12k\pm1$ (i.e. 11,13, 23, 25, 35, 37…) will exist at the Tx primary, and $I_h/I_1=1/h$ is simply the reciprocal of h which is rather small at high h values.
(I_1 is the fundamental 50Hz Tx current.)

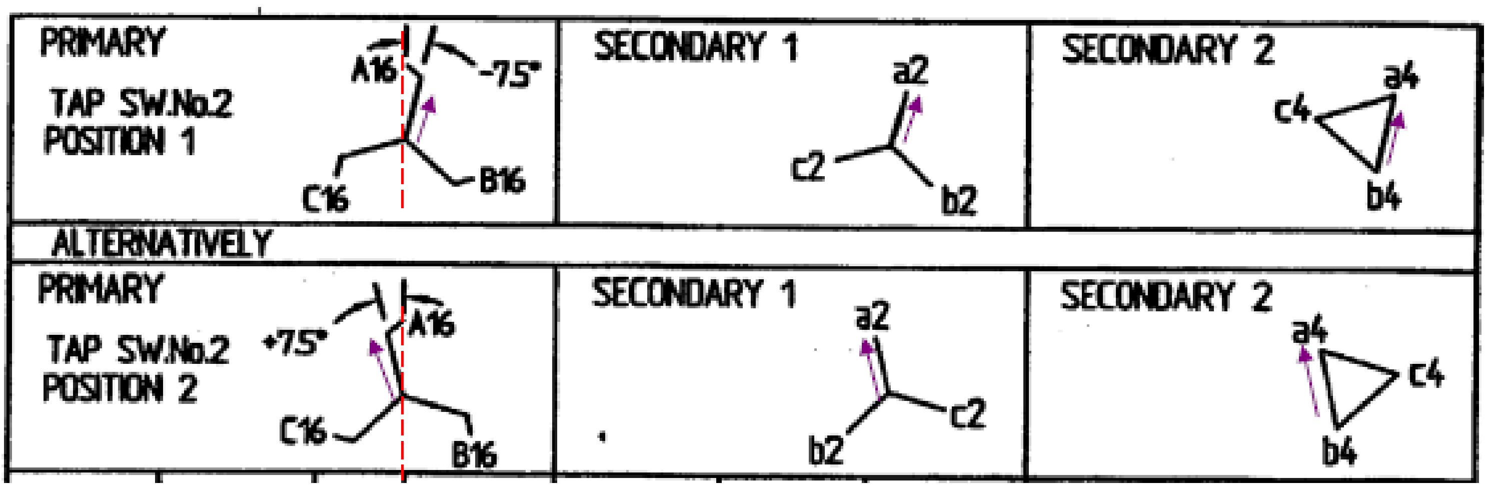
In 24-pulse rectifier, I_h for h= 11, 13, 35 & 37 are further suppressed.

24-pulse rectifier in DC traction system

In MTR, the each 1.5kV source is a pair of Tx rectifier of 12-pulse each. These Tx are connected to 33kV systems (of both CLP and HEC), in which they are **split** to avoid power circulation.



Each Tx has zig-zag primary winding, such that one Tx winding of –7.5° phase shift and the other +7.5° (by means of phase shift change switch), i.e. an angle difference of 15 °



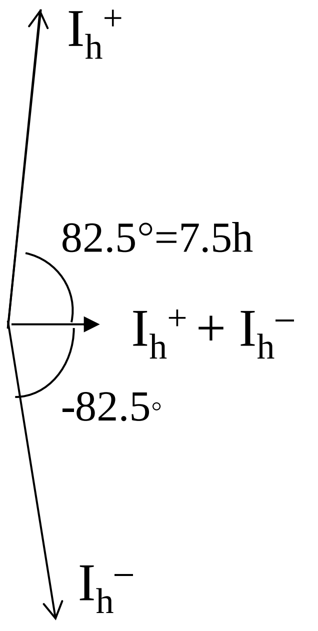
Then V_{DC} will be of 360/15 =24 pulse.

Each Tx has 2 secondary windings (star and delta).

Harmonic suppression by 24-pulse rectifier

The two primary current have an angle difference $\Delta\theta_1$=7.5-(-7.5)= 15° at 50Hz, and $\Delta\theta_h$=7.5h-(-7.5h)=15h° at harmonic frequency, given by:

h	11	13	23	25	35	37
15h	165	195	345 (-15)	375 (15)	525 (165)	555 (195)
|RF|	0.13	0.13	0.99	0.99	0.13	0.13



Current sum of 2 Tx for h=11

For h=11, 7.5×h=82.5°, 82.5°×2=165°

Reduction factor (RF)

RF = cos82.5°=0.13, and similarly for h=13, 35 & 37.

Thus, only 23th and 25th harmonics can only be rich in the 24-pulse rectifier with magnitude I_h/I_1=1/h.

In MTR, the high harmonic injection to PCC is very unlikely, but the hazard of harmonic resonance beyond PCC for all h (due to B of 33kV cable & 33kV cap) still exists.

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Summary of major observations

For 25kV, two types of resonance associated with ac traction harmonic are:

At series resonance,

-$X_L \approx X_C$ and max $I_F = I_S$, $|V_C + V_L|$ is much smaller than $|V_C|$ or $|V_L|$, implying voltage resonance.

However, as train harmonic I_S is foreseeable, voltage resonance is 'controllable' by tuning at n (where n<h), and the amount of filter absorption of I_F can be controlled.

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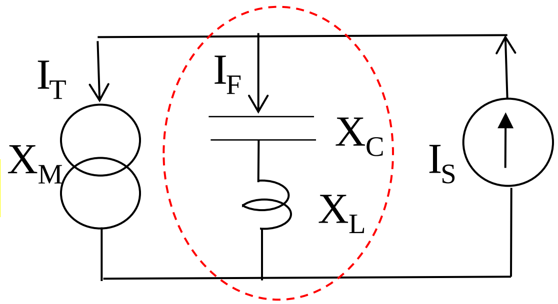

$X_M = X_T + X_{SYS}$

So long taking $s = V_{max}/V_{cap} + XL\omega Cp$ in the filter design, equipment insulation failure due to voltage resonance should not occur.

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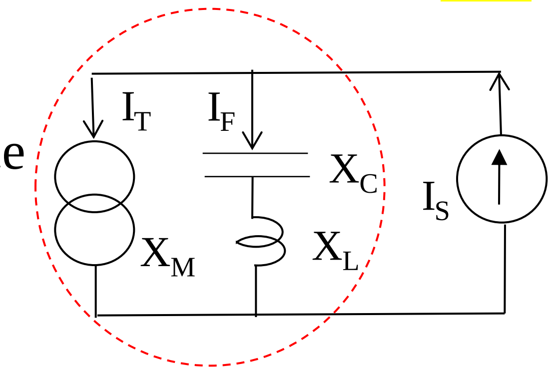
At parallel resonance,

-$X_M \approx X_C + X_L$, and $I_F >> I_S$ (can be > 100) $\Rightarrow$ current resonance

Both V_L & V_C can be of large values $\Rightarrow$ voltage resonance



Since X_M consists of Tx and 132kV system circuits as well as fault level, when will this resonance occur is uncertain.

From analyses, parallel resonance should not occur for 3th harmonic filter, even 50n is tuned close to 150Hz (to increase absorption), but not for filter of harmonics 5th, 7th .., nor for multi-leg filter.

For 132kV, both series (slide-21) and parallel resonances (slide-26) are 'uncontrollable'.

Comments on harmonic impact on the 4 local railway systems (1)

1. East Rail (25kV 1-ph)
Mainly low order harmonics and h=3 dominant. The problem can be solved with passive filter tuned closed to 150Hz and with proper filter rating according to foreseeable total harmonic current I_S. Harmonics issues becomes complicated with IKK (trains of unity power factor) that over-compensation and over voltage will occur, but the advantage is that 3rd and 5th harmonics from IKK will be anti-phase to (i.e. cancel) those from conventional train. Capacitors will likely experience overvoltage due to over-compensation and inadequate capacitor design of $s=V_{max}/V_{cap}$.

2. West Rail (25kV 1-ph)
Because of the unity power factor drive of IKK, both low- and high-order harmonics exist. With the conflicts of (a) over-compensation and over-voltage and (b) low harmonic amplification (or even resonance), passive filter cannot be installed. Since the technique of HV active filter is not yet mature, no pragmatic measures can be recommended.

Comments on harmonic impact on the 4 local railway systems (2)

3. Automated People Mover (600V 3-ph)
Rich in low-order harmonic with the absence of 3 and 3-multiples. Multi-leg filter (5, 7 & 11) has once been installed, and lower order harmonics must be amplified. The final solution was to replace the multi-leg filter by 600V 3ph Active Filter.

4. Mass Transit Rail (1.5kV DC)
Mainly h=23 & 25 with magnitude of I_1/h. Magnitudes of h=11, 13, 35 & 37 are further reduced to 13% of I_1/h by the 24-pulse rectifier Tx. Very heavy harmonic injection to PCC should not occur.

In all above 4 cases, there is a potential hazard of parallel resonance beyond PCC, even the traction harmonic injection is small. If it really happens, the role of responsibility should be the supply utility, not MTRC.

Impact of Imbalance due to Single-Phase Traction Load

Extracted from IEEE/HKIE seminars

More Proper and Economic Design of Shatin-Central-Link, 2012 Nov14,

&

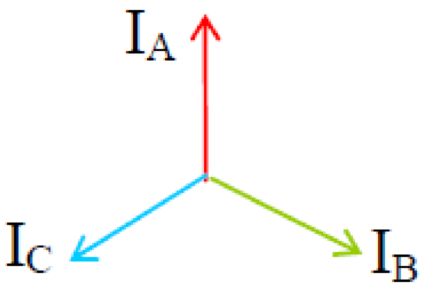
Impact of Imbalance of Single-Phase Traction to Three-Phase Power System, 2010 Dec-7.

Supply Rule from CLPP Website

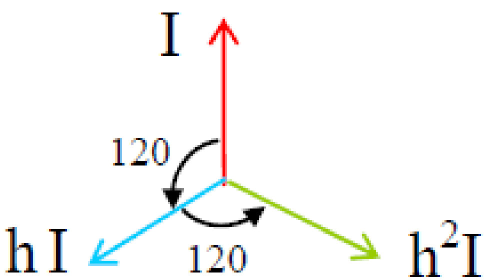
Type of Distortion	Type of Abnormal Load	Operational Limit
Voltage Fluctuation	Electric arc furnace	• for 132kV and below 2 %
	Motor starting	• Infrequent (intervals exceeding 2 hours) 3 % • Frequent (intervals not exceeding 2 hours) 1 %
	Rolling mill and traction (motor starting intervals not exceeding several minutes)	• Step-type change : up to 66kV 1 % 132kV ¾ % • Ramp-type change : up to 66kV 1 % /sec 132kV ¾ % /sec • Limit of total change : up to 66kV 3 % 132kV 2¼ %
Voltage Unbalance	Single phase electric traction load	• Voltage : negative sequence 2 % of positive sequence • Current into generators : negative sequences 5 % of positive sequence

25kV ac traction is of single phase and imbalance is inevitable

Balanced 3-phase load



The 3- phase current is $I_P=[I_A, I_B, I_C]$. For balanced loading, they are of equal magnitude and spaced by 120°



Using operator $h=\angle 120^\circ$, and let $I_A=I\angle 0$ be the reference, then the 3- phase current are $[I_A, I_B, I_C]=[I, I\angle 240^\circ, I\angle 120^\circ]=[I, h^2I, h\,I]$

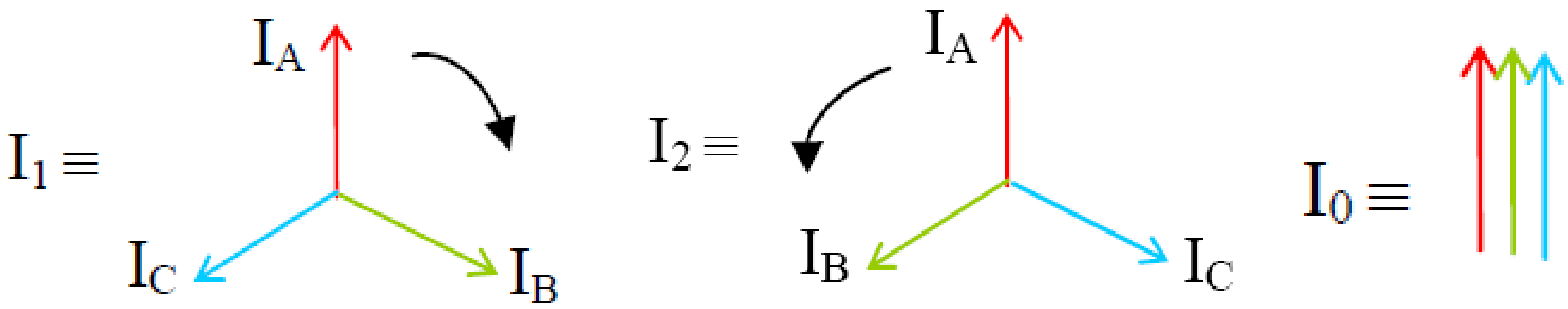
Mathematically, the *p*hase current $[I_P]=[I_A, I_B, I_C]$ can be transformed to *s*equence current $[I_S]=[I_0, I_1, I_2]$, using T-matrix

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & h & h^2 \\ 1 & h^2 & h \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}$$

In short: $[I_S]=[T]\,[I_P]$, where $[I_0, I_1, I_2]$ are respectively zero-, positive- and negative-sequence current.

Physical interpretation of I_1, I_2 and I_0

3-phase power supply provides only positive sequence voltages $[V_A, V_B, V_C]$. If the 3-phases have equal load, it is balanced.
The balanced 3-ph current $[I_A, I_B, I_C]$ can be represented by a single component I_1 (clockwise), the positive sequence current.

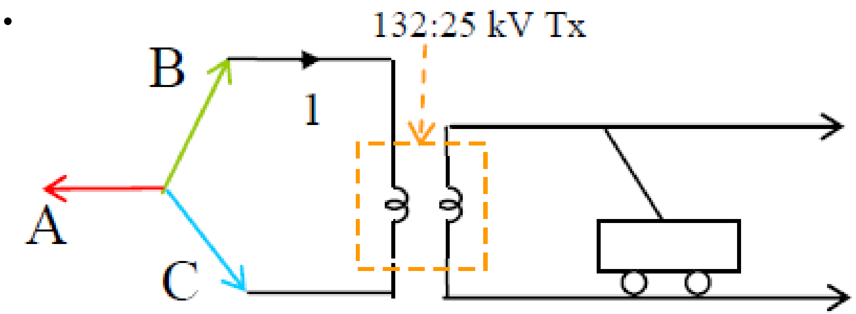


For unbalanced load, the 3-ph current will have two more sequence components: I_2 and I_0.

I_2 (anti-clockwise) is the negative sequence current, and
I_0 (stationary) is the zero sequence current.

Single 1-ph Traction load (B-C)

High voltage 132kV has no neutral wire.
The ac traction has three types of load current [I_{AB},I_{BC},I_{CB}].
Assuming the traction supply current at 132kV is 1-unit connected to *B-C* phase,
The imbalance is then [1].



$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \tfrac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & h & h^2 \\ 1 & h^2 & h \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix} \Rightarrow \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 1 \\ 0.577\underline{/90^\circ} \\ 0.577\underline{/-90^\circ} \end{bmatrix}$$

The imbalance defined by $|I_2|/|I_1|$=0.577/0.577=100%.

(Without neutral wire, I_0 is always zero.)

Double 1-ph Traction loads (B-C and A-B)

If a feeding station (FS) supplies two sections with two different phases, say *B*-*C* and *A*-*B*, then [1,2]

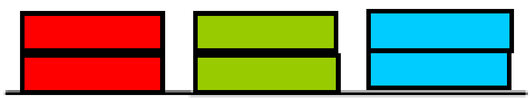
$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \tfrac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & h^2 & 1 \\ 1 & h & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix} \Rightarrow \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 1 \\ 0.577\angle 90^\circ \\ 0.577\angle -90^\circ \end{bmatrix}$$

The imbalance is reduced to 0.577/1.155=50%. Thus in KCR, a FS must have at least two on-load transformer (Tx), e.g. Tai Wai FS has 2 sections: north to Tai Po Kau and south to Hung Hom.

The above imbalance calculation is for **pure** ac traction load.
The resulting unbalanced voltage V_2 will affect other consumers connected to point of common coupling (PCC) at 132kV.
With other consumer loads (almost balanced), V_2 in should be much reduced, less than 0.11pu [1], within the CLP limit of V_{2MAX}=2%.

However, overall imbalance is critical to generator, and CLPP has set a limit of 5%.

Overall Imbalance vs Number of Rail Section

Number of sections	Phase connections *AB* *BC* *CB*	Imbalance $\lvert I_2 \rvert / \lvert I_1 \rvert$
1		100%
2		50%
3		0%
4		25%
5		20%
6		0%

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Summary of Imbalance vs Number of Section

(a) Section	1	2	3	4	5	6	7	8	9	10
(b)Imbalance	100%	50%	0	25%	20%	0	14%	13%	0	10%
(a)×(b)	1	1	0	1	1	0	1	1	0	1

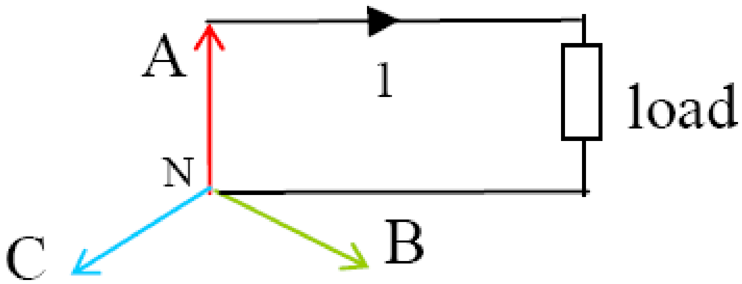
The imbalance for 3 or 3-multiple is zero.
The imbalance for non-3-multiple decreases with more sections.

In 80's, ERL has only 4 sections and the overall imbalance is 25%.

The above estimations assume each section has identical train load. 25

Imbalance due to traction load is inevitable. Although imbalance does not affect the train operation, a competent engineer in the power utility should reduce the imbalance, as far as possible, based of parameters provided by the mass transit company **at the planning stage**. These parameters include number of car per train, number of section in a line, total line length, headway (i.e. train frequency).

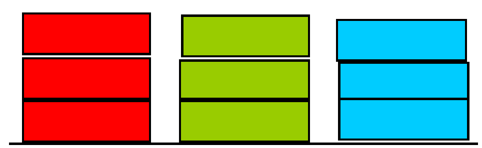
Imbalance in Domestic Building (1)



With neutral wire N, the three types of load are: I_{AN}, I_{BN}, I_{CN}

To minimize the imbalance, an engineer should evenly shares load to each phase at design stage.

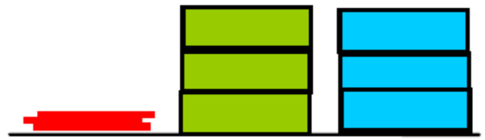
For a 9-floor building, a design of phase/floor allocation can be:

	Phase connection		
	AN	BN	CN
floors	1,2,3	4,5,6	7,8,9
			

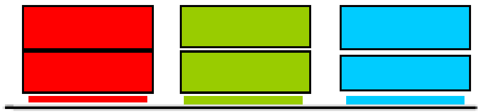
If the electricity consumption of each floor is identical, perfect balance can be achieved (i.e. 0% imbalance).

Imbalance in Domestic Building (2)

However, if floors 1,2,3 are car-park with lighting load only, imbalance occurs.

	Phase connection		
	AN	BN	CN
floors	**1,2,3**	4,5,6	7,8,9
			

A competent engineer should assign the phase connections as, say:

	Phase connection		
	AN	BN	CN
floors	**1**,4,5	**2**,6,7	**3**,8,9
			

If the upper floor loadings are equal, the imbalance is almost zero.
In reality, the engineer does not have loading information of the floors at design stage. But he should realize the car park must of much lower electricity consumption.

If one groups all car park load to one phase, and insists he has evenly allocated 3-3-3 to the 9 floors, he is unprofessional.

Traction Load Estimation at Design Stage (1)

In ac traction design, the traction load of each line section depends on the line length, number of sections, the train headway (peak or off-peak), the number of cars in each train; all information are ready at design stage. (The number of passengers per car can only be obtained by forecast.)

KCR system parameters at peak load

System	Car	Length (km)	Headway (min)	Section	Load Ratio	
					Tx	System
ERL	12	40	2.5	4	1.0	4
MOL	4	12	3	1	0.33	0.33
WRL	7	34	3	5	0.33	1.65

Assumptions [1,2]

1. Tx current will be proportional to the number of car and the length of the system, but is inversely proportional to the headway and the number of section.
2. Tx in the same system are assumed of equal loading.
3. For simplicity, each Tx in ERL is assumed to have a current of 1 unit.

Traction Load Estimation at Design Stage (2)

KCR system parameters at peak load

System	Car	Length (km)	Headway (min)	Section	Load Ratio	
					Tx	System
ERL	12	40	2.5	4	1.0	4
MOL	4	12	3	1	0.33	0.33
WRL	7	34	3	5	0.33	1.65

Observation

1. The ratio of system loadings of ERL:MOL:WRL is 4.0:0.33:1.65=12:1:5.
2. Ma On Shan Line (MOL) has only one section (or Tx) and the imbalance is inevitably 100%. However, its loading is only 1/12 of ERL, and the impact on overall imbalance is the smallest.
3. ERL has the highest loading, and its impact on overall imbalance (critical to generator with limit of 5% only) is the highest.

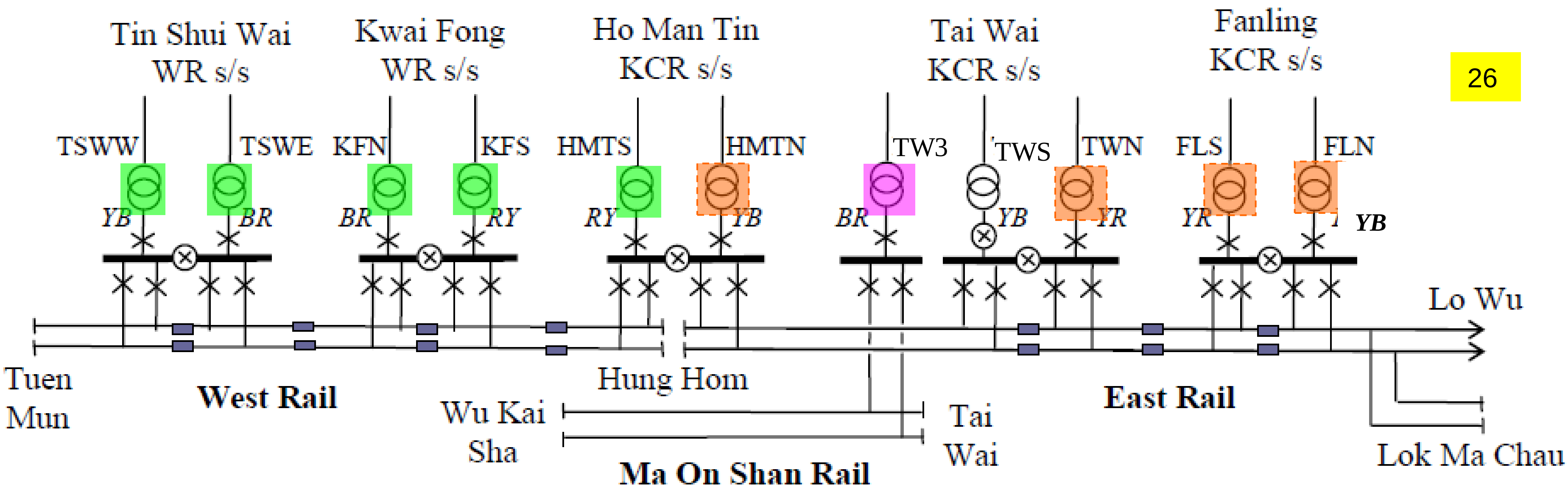
KCR system in 2010, with three lines and 5 substations

Total 10 Tx in KCR system [1,2]:

ER Line has 4 Tx in 3 s/s

MO Line has only 1 Tx

WR Line has 5 Tx in 3 s/s



HMTN and TW**S** are of same phase (*Y*-*B*), but there is no track section cabin (TSC) between them. Therefore, one Tx (TWS) is at standby.

All Tx are of 26.5MVA rating, except TWN and TWS upgraded to 38MVA in 2009.

(Phase only depicts the 25kV Tx secondary winding connection. Other standby Tx are not shown for simplicity)

Imbalance for Ten Sections in KCR 2010 [1]

Tx loading and current imbalance in KCR system in 2010

Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	FLS [1]	FLN [1]	
Tai Wai	TWN [1]		TW3 [0.33]
Ho Man Tin	HMTS [0.33]	HMTN [1]	
Kwai Fong	KFS [0.33]		KFN [0.33]
Tin Shui Wai		TSWW [0.33]	TSWE [0.33]
Current Imbalance	ERL [2-2-0]		50%
	WRL [0.67-0.33-0.67]		20%
	Overall [2.67-2.33-1]		25.5%

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(Conventional color code for phases A-B-C is red-yellow-blue (*R*-*Y*-*B*).

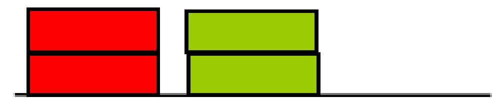
The phase allocation to RY, YB and BR is 4-3-3 and appearing perfect.
It is surprised to see that the imbalance of 25.5% for 10 sections was even worse than the 25% in late 80's when there were only 4 sections. 25

The main reason was due to the swap of phase connection of ERL in 2004.

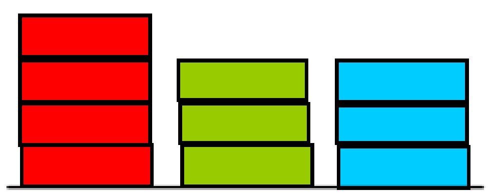
Phase Swap at Tai Wai FS in 2004

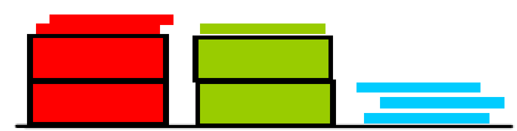
ERL is the dominant line in KCR with 3 times Tx loading to those in other lines. Before 2004, ERL had 3 types of phase connections. Since 2004, it had only 2 types..


ERL before 2004


ERL since 2004

However the Utility C-Engineer claimed he only concerned the imbalance of entire KCR (rather than a single line) and he had most evenly allocated 4-3-3 to the ten Tx.


4-3-3 phase connection


Actual loading of 10Tx

It appears he had ignored the relative loading of the section, which can be easily derived from the design parameters at planning stage that the ERL Tx should have much higher load.

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Suggestions for More Proper Design of KCR

Stage IIa: Change HMTN from ***Y-B*** to ***B-R***

Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	FLS [1]	FLN [1]	
Tai Wai	TWN [1]		TW3 [0.33]
Ho Man Tin	HMTS [0.33]		**HMTN [1]**
Kwai Fong	KFS [0.33]		KFN [0.33]
Tin Shui Wai		TSWW [0.33]	TSWE [0.33]
Current Imbalance	ERL [2-1-1]		25%
	WRL [0.67-0.33-0.67]		20%
	Overall [2.67-1.33-2]		19.2%

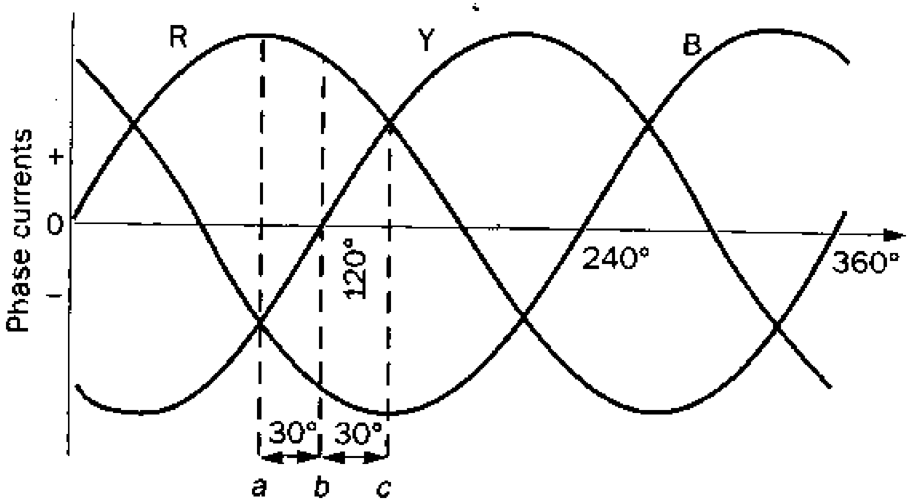
Suggestion had been made in [1] to properly re-phase the sections in two stages to evenly distribute the train load.

Theoretically, zero imbalance may be achieved.

Stage IIb: Change Tx pair HMTS/KFS from ***R-Y*** to ***Y-B***			
Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	FLS [1]	FLN [1]	
Tai Wai	TWN [1]		TW3 [0.33]
Ho Man Tin		**HMTS** [0.33]	HMTN [1]
Kwai Fong		**KFS** [0.33]	KFN [0.33]
Tin Shui Wai		TSWW [0.33]	TSWE [0.33]
Current Imbalance	East Rail [2-1-1]		25%
	West Rail [0-1-0.67]		**52.9 %**
	Overall [2-2-2]		**0%**

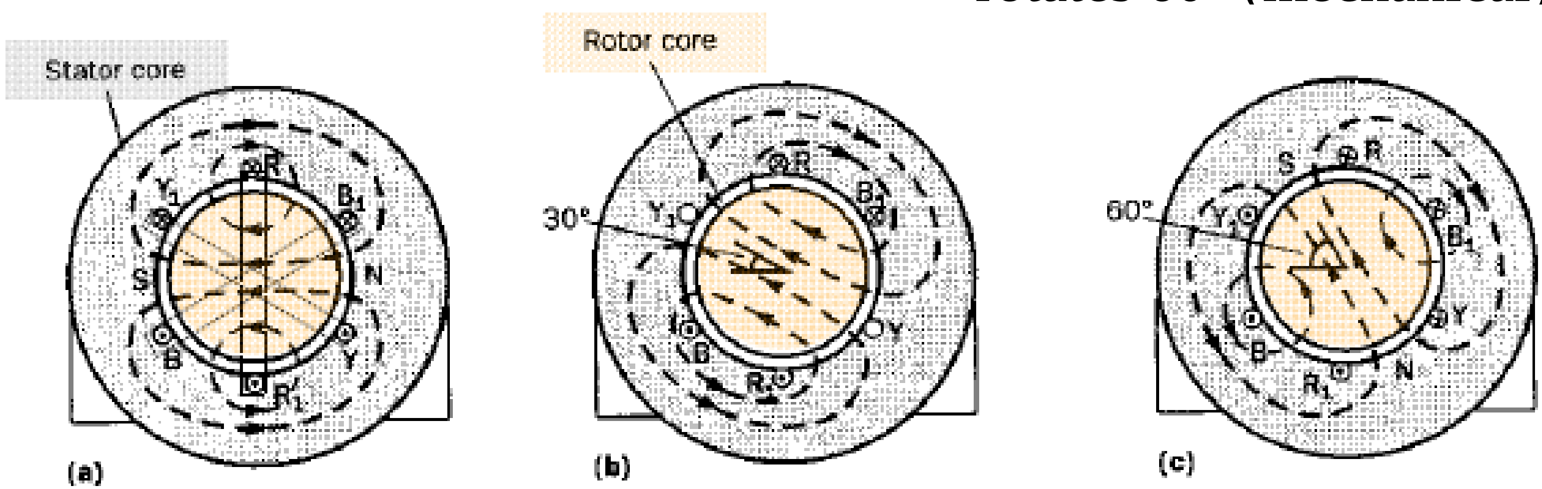
However, as traction load fluctuates, the imbalances (although not zero) must be much reduced by this re-phasing.

Rotating Field of 3-ph Machine



The stator balanced current I_1 establishes a field rotating clockwise (i.e. forward).

As the stator current advanced 60° (electrical), the stator field F_1 rotates 60° (mechanical).



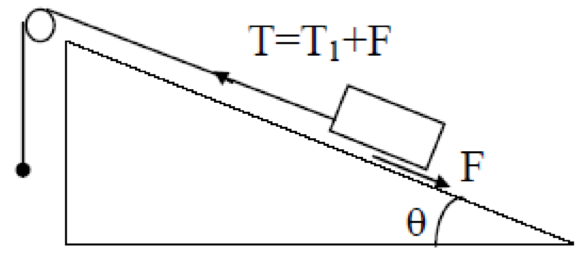
Distribution of magnetic flux due to 3-phase current (using right-hand rule)

The stator field F_1 induces I_1' in rotor windings which establishes another field F_1' (not shown in the above diagram).

Energy Loss with Friction

Frictional loss in linear motion

Consider a mass M pulled up along a rough slope. The total tension is $T=T_1+F$, where $T_1=Mg.\sin\theta$ and F is frictional force opposing the motion. The energy to pull the mass is increased due to Friction.



The extra energy will be dissipated as heat generated by friction.
If the slope is very rough, the heat may cause damage to the mass.

If a generator has unbalanced loading, extra energy is required to overcome the negative torque. This energy will be dissipated as iron losses (eddy current and hysteresis), causing severe damage to the rotor [2]. 37

To protect the generator from the severe damage, the generator will trip if current imbalance exceeds a certain limit. (In CLPP, the limit is 5%.)

The extra energy input reduces the generation efficiency. Very often it is regarded as generator loss.

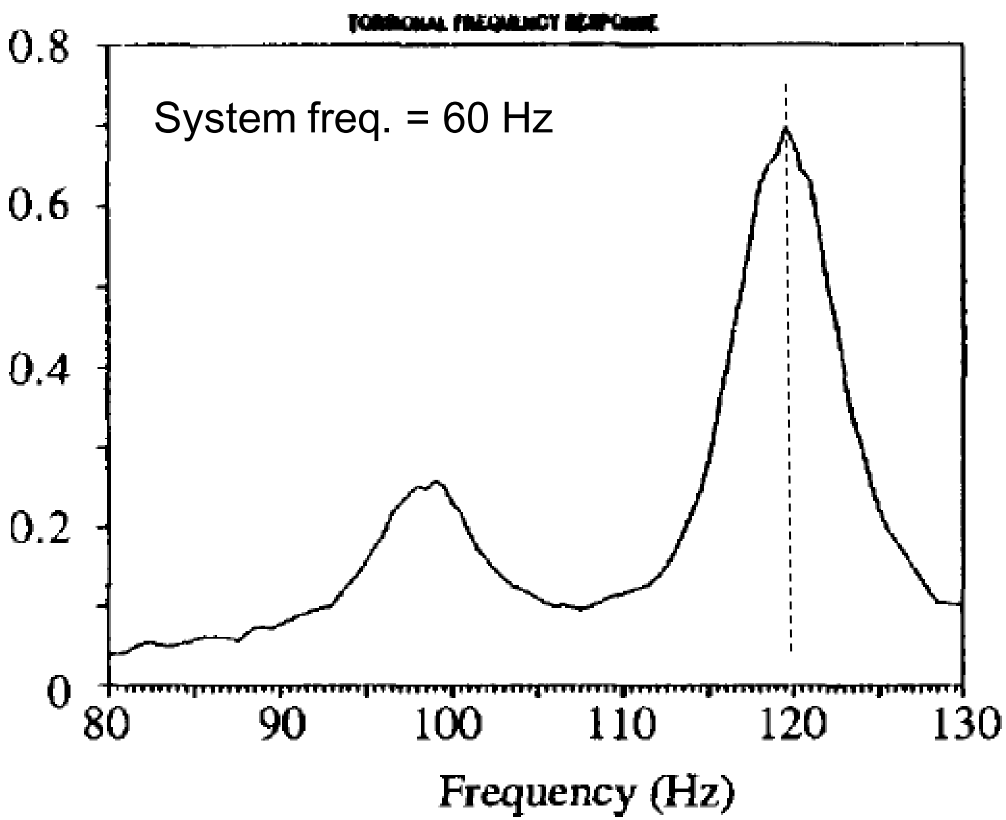
Impact of Damper Winding Current to Rotor [1,2]

The damper current I_{2D}' is similar to the positive sequence current, except that the resulting reaction field rotates counter to the dc field system and hence produces a flux which cuts the rotor at twice the rotational velocity, thereby inducing double frequency currents in the field system and in the rotor body, creating additional hysteresis loss P_h and eddy current loss P_e. In general, both $P_h = k_h f B_m^x$ and $P_e = k_e f^2 B_m^2$ will increase with the frequency f.

The resulting eddy-currents (proportional to f^2) are very large and cause severe heating of the rotor. So severe is this effect that a single-phase load equal to the normal 3-phase rated current can quickly heat the brass rotor slot wedges to the softening point; they may then be extruded under centrifugal force until they stand above the rotor surface, when it is possible that they may strike the stator iron. Overheating of the wedges may be sufficient to anneal them enough to result in rupture in shear. Concentration of heating occurs on portions of the coil binding rings and here surface fusion has been known to occur.

I_2 Impact: Super-synchronous Resonance to Turbine Blade [2]

Other than the above well known adverse effects, turbine blade super-synchronous resonance is one of the most serious problems. The severity of negative sequence current problems resurfaced after the turbine blades of a nuclear power plant in a country of Southeast Asia were broken and almost caused a severe nuclear disaster.



It was because the double frequency component of I_2 may match the mechanical resonance of the turbine blades due to the frequency deviation and induce the supersynchronous resonance.

Impact of Current Imbalance to Energy Consumption

The negative sequence current I_2 creates a stator field (of double frequency $2f_0$) rotating in opposite direction to the rotor motion, which will downgrade generator performance and efficiency, overheat the rotor. For a total generation of, say 6000MW, a very slight increase of, say, 0.1% generator output (e.g. to cover the additional losses) represents an undue increase of 6MW.

If a system generation is equally shared by nuclear, gas and coal, the overall generation efficiency roughly equals to (0.33+0.55+0.35)/3=0.41, and the increase of rate of fuel waste will be amounted to 6/0.41=14.6MW. This extra increase of fuel cost will be shared by all consumers at large.

Usually, the ac traction load is a small fraction of the total system generation and a small percentage decrease in generator efficiency may not be noticeable. For instance, in 2009, the CLPP demand is 6389MW and the 30-minute average peak demand of KCR is about 64MW.

Case studies here are based on simplified assumptions/data of KCR. Without the CLPP generator parameters and the realistic imbalance data, it is impossible to estimate the actual energy waste due to the traction imbalance.

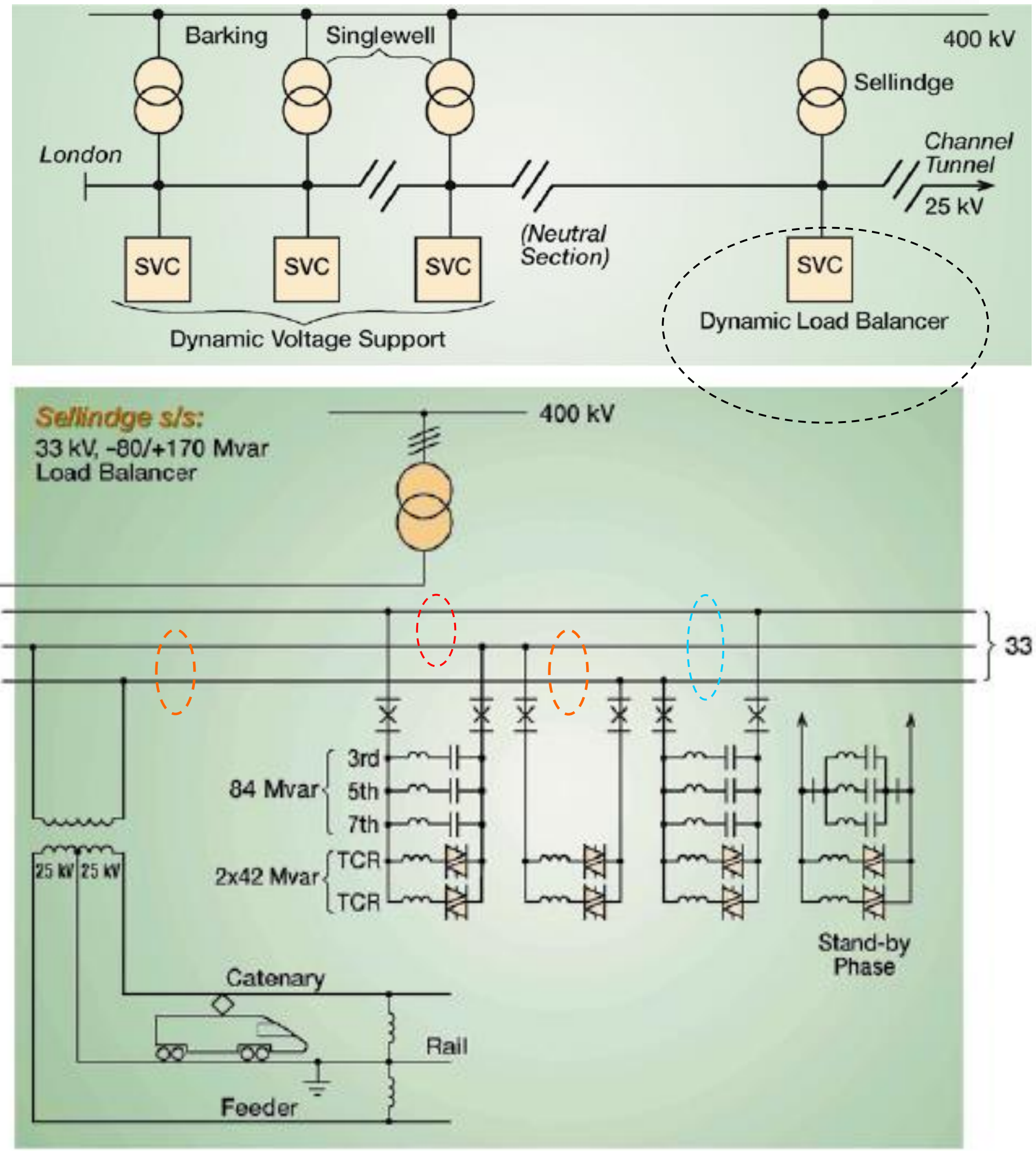
Combating Imbalance by 33kV Dynamic Load Balancer [5]

Installed at high-speed rail of Channel Tunnel Rail Link at Sellindge s/s near Dover.
Rail length 109 km between London and Paris.
Total time travel: 2hr 20min.

(HK-GZ 150-km within 2hr.)

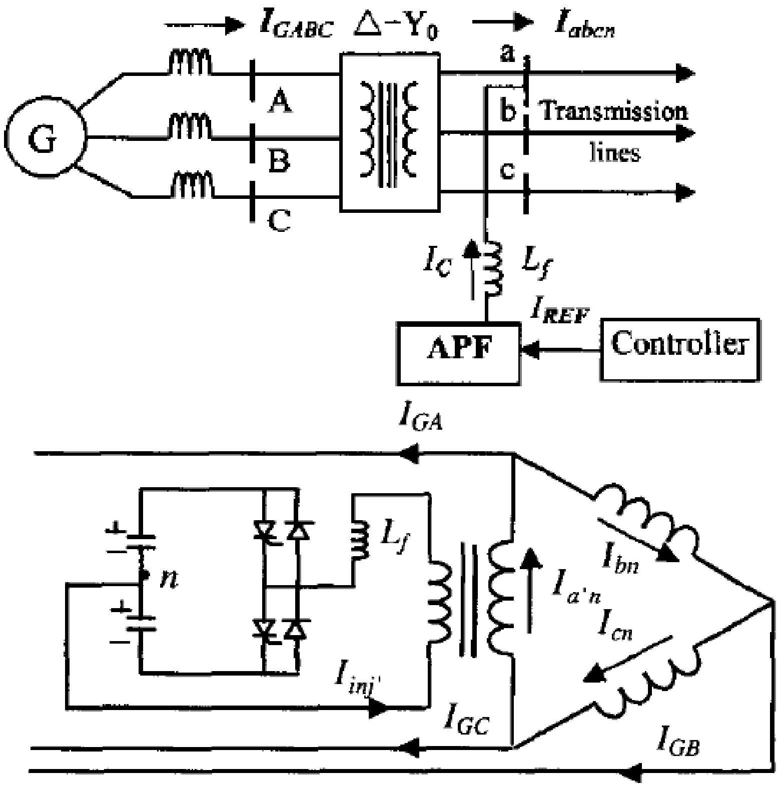
The Balancer is regarded as an asymmetrical controlled stator var compensator (SVC).

The Balancer is controlled to compensate I_2 drawn from 400kV and to regulate power factor to unity.

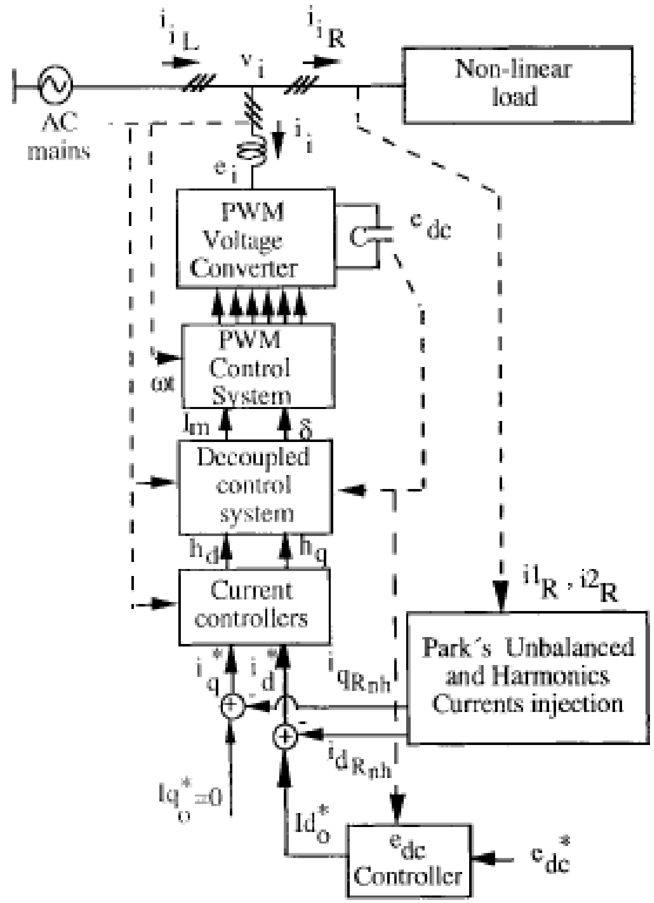


Combat Imbalance by Active Power Filter [2]

Active power filter based on voltage source inverter



Active power filter with unbalance current control



However, all these combating methods are complicated, and installation/operation costs are very high.

In KCR, the most cost effective is the re-phasing the Tx

Stage IIa: Change HMTN from ***Y-B*** to ***B-R***

Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	FLS [1]	FLN [1]	
Tai Wai	TWN [1]		TW3 [0.33]
Ho Man Tin	HMTS [0.33]	→	**HMTN [1]**
Kwai Fong	KFS [0.33]		KFN [0.33]
Tin Shui Wai		TSWW [0.33]	TSWE [0.33]
Current Imbalance	ERL [2-1-1]		25%
	WRL [0.67-0.33-0.67]		20%
	Overall [2.67-1.33-2]		19.2%

Stage IIb: Change Tx pair HMTS/KFS from ***R-Y*** to ***Y-B***

Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	FLS [1]	FLN [1]	
Tai Wai	TWN [1]		TW3 [0.33]
Ho Man Tin	→	**HMTS** [0.33]	HMTN [1]
Kwai Fong	→	**KFS** [0.33]	KFN [0.33]
Tin Shui Wai		TSWW [0.33]	TSWE [0.33]
Current Imbalance	East Rail [2-1-1]		25%
	West Rail [0-1-0.67]		**52.9 %**
	Overall [2-2-2]		**0%**

Suggestion had been made in [1] to properly re-phase the sections in two stages to evenly distribute the train load.

Theoretically, zero imbalance may be achieved.

However, as traction load fluctuates, the imbalances (although not zero) must be much reduced by this re-phasing.

Conclusion (1)

AC traction is of single phase, and imbalance to 3-phase supply is inevitable. According to the supply rule of CLPP, the limit is 2% for voltage imbalance at substation and 5% for current imbalance at generator.

CLPP has regularly monitored the negative sequence voltage V_2 of 132kV traction supply at point of common coupling (PCC). V_2 is well within the 2% voltage limit because CLPP 132kV system is very stiff, and voltage imbalance is no longer a problem in CLPP system. Impact of only current imbalance is of concern for power system operation.

ERL may be the only single-phase traction system (having three or more transformers) in the world that has over 50% current imbalance by itself. ERL appears ridiculous in design since it is the largest ac traction system in CLPP.

KCR is the second largest consumer load in CLPP, but its average load is only about 1% of the CLPP system total. Although generator tripping due to ac traction load is unlikely, there is a possible hazard of super-synchronous resonance, leading to turbine blade damage.

Conclusion (2)

Moreover, the negative sequence current will create a rotating field opposite to generator rotor motion, inducing a double frequency current in the rotor and the much increased iron losses will heat the rotor, jeopardizing the generator performance/efficiency, resulting an undue increase of fuel consumption.
The extra cost of fuel consumption will be shared by all customers.

To eliminate the design ‘abnormality’, to enhance generator efficiency and performance, and to avoid the unnecessary waste of energy, pragmatic remedial measures have been proposed to appropriately rearrange the 132kV phases connecting the traction transformers in local traction substations.
It is expected the overall current imbalance will be much reduced (to even zero).

If an energy saving measure is beneficial to both consumers and utility, as well as cost-effective, it is expected a reputable utility will take immediate action for rectification.

IEEE

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Seminar

Impact of Traction Harmonics to Power System

Delivered by Dr C T Tse

Nov-14, 2011 (Mon)

FJ303, PolyU

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Power quality issues

Requirements of Customer's Equipment

(Supply rule 2000 from CLP website)

Type of Distortion	Type of Abnormal Load	Operational Limit
Voltage Fluctuation	Electric arc furnace	• for 132kV and below 2 %
	Motor starting	• Infrequent (intervals exceeding 2 hours) 3 % • Frequent (intervals not exceeding 2 hours) 1 %
	Rolling mill and traction (motor starting intervals not exceeding several minutes)	• Step-type change : up to 66kV 1 % 132kV ¾ % • Ramp-type change : up to 66kV 1 % /sec 132kV ¾ % /sec • Limit of total change : up to 66kV 3 % 132kV 2¼ %
Voltage Unbalance	Single phase electric traction load	• Voltage : negative sequence 2 % of positive sequence • Current into generators : negative sequences 5 % of positive sequence

Harmonic Voltage Distortion	Electric arc furnace	• At 132kV or above odd harmonic distortion 1 % total harmonic distortion 1½ % • At 66kV or 33kV odd harmonic distortion 2 % total harmonic distortion 3 % • At 11kV odd harmonic distortion 3 % total harmonic distortion 4 %
Harmonic Current Distortion	Other Non-linear Equipment with size 'I' in Ampere	• At 380V/220V total odd harmonic distortion: I < 30A 20 % 30A ≤ I < 300A 15 % 300A ≤ I < 600A 12 % 600A ≤ I < 1500A 8 % I ≥ 1500A 5 % total even harmonic distortion: 25 % of the odd harmonic limits

Appears to have no harmonic current limits at 132kV

Major 'Abnormalities' due to AC traction

1. Voltage fluctuation
2. Voltage dip (V_{min} is 17.5kV)
3. Voltage and Current Imbalances
4. Voltage and Current Harmonics
5. Interferences with signalling and communication system (to be discussed in EE537).

(6). Low power factor

In order to apply for the economic (bulk) tariff, the traction operation has to comply with the regulation/limits imposed by the power utility with respect to items 1, 3, 4 & 6, at the point of common coupling (PCC), e.g. Fanling 132kV

- AC Traction is the only consumer that contributes all the above 'abnormalities'.

Remedy

- Install booster transformers
- sectionalize the railway system
- install capacitor compensator/filter at strategic locations

(to be discussed in EE533)

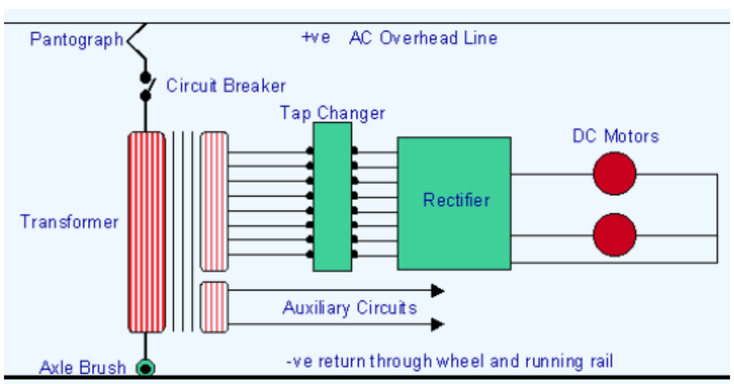
Traction Harmonics

Harmonic Source
AC & DC drives

Adverse Effect of Harmonics
Overheating of conductors
Overheating of electrical equipment
Mechanical oscillation of electrical machine
Telecommunication interference
Inaccurate meter readings
Disturbance to sensitive electronic equipment
False operation of protection equipment

Standards
Engineering recommendation G5/3, G5/4
IEEE standard 519-1992

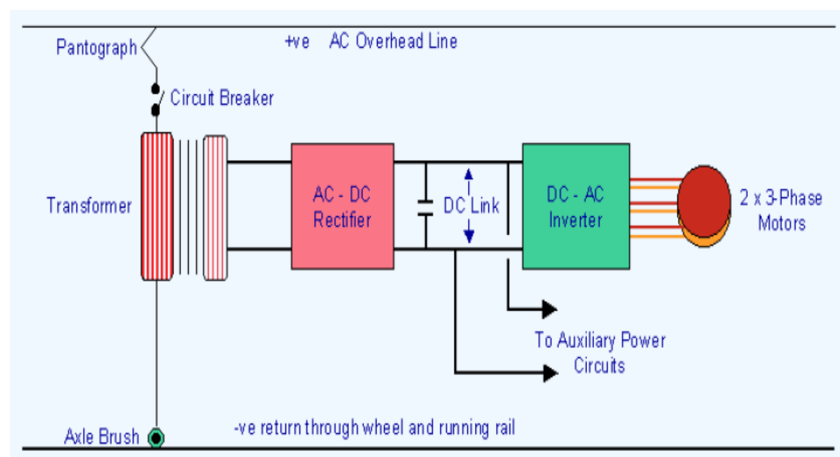
AC Locomotives with Tap Changer Control



Power collected by pantograph and passed to transformer
25kV stepped down and then rectified to acceptable voltage for motor (dc)
Current controlled by Tap Changer (instead of conventional resistor)

(DC traction motor has many problems.)

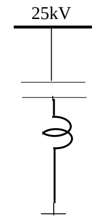
AC Locomotives with PWM Control



Single phase 50Hz AC (after rectification) becomes 3-phase AC with variable voltage and variable frequency (VVVF), supplying 3-ph motors.

Harmonic current in electrified ac system

KCR electrification began in 80's but with very poor power factor. Capacitors were installed in Tai Wai 25kV for pf improvement



In the early stage, train drives were of tap-changer type and 3rd harmonic (h=3) dominant. The installed cap bank was then modified to add series reactor to become third harmonic filter.

Harmonic increased with the introduction of thyristor type drive. With the advances of power electronics, the speed and traction force of new drives are much enhanced but the harmonics are much increased.

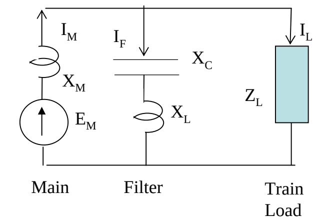
Dual functions of 3rd harmonic passive filter in East Rail

It provides capacitive compensation at 50Hz and also absorbs harmonics of $h \geq 3$.

System representation at fundamental frequency

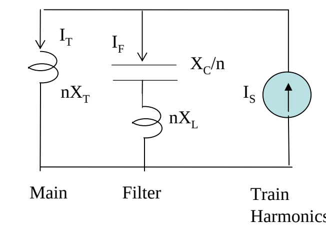
Main supply (50Hz) is represented by Thevenin equivalent (E_M & X_M).
Load represented by impedance $\mathbf{Z}_L$
The shunt filter (connecting in parallel with load) provides capacitive compensation.

(In ac traction, X_M includes transformer X_T and system X_{SYS} and usually $X_T >> X_{SYS}$)



System representation at frequency 50n (Hz)

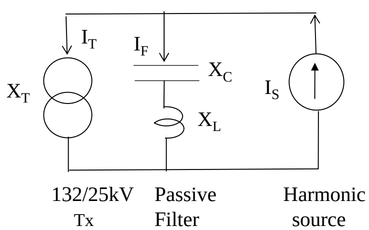
Main is represented by single inductance nX_T without emf, since it is a 50Hz source only.
The harmonic produced by the train is often represented by Norton ($\mathbf{I}_S$ and $\mathbf{Y}_S$), and very occasionally by Thevenin ($\mathbf{V}_S$ and $\mathbf{Z}_S$).
Since $\mathbf{Y}_S$ is a very complicated function, $\mathbf{Y}_S=0$ is usually assumed (most pessimistic assumption for Norton).

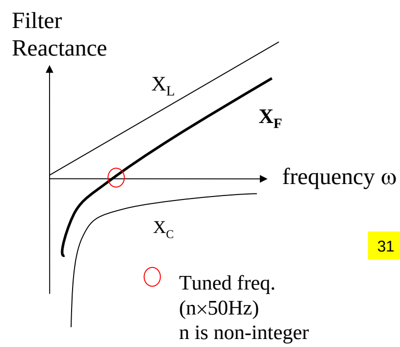


(In subsequent harmonic diagrams, n may be skipped for simplicity.)

Harmonic current sharing between Transformer and Filter (at 25kV)

16





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Filter reactance

$$X_F = X_L + X_C = \omega L + (-1/\omega C)$$

I_S shared between X_T and X_F

13 $I_T = I_S\, X_F / (X_T + X_F)$

12 $I_F = I_S\, X_T / (X_T + X_F)$

The tuned (resonant) freq. must be less than the targeted harmonic freq. (i.e. n<h)

The smaller X_F, the less I_T flow to the PCC, and the larger I_F (filter more harmonic absorption)

Worked Example on early shunt filter (passive)

A 25kV traction load is of low power factor and is rich in third harmonic. Design a shunt filter tuned at 125Hz which can also provide 4MVAr capacitive compensation at 50Hz.

Solution

At 50Hz: $\omega=2\pi 50$, $X_L=\omega L$ and $X_C=-1/(\omega C)$

$Q=V^2/X_F \Rightarrow X_F=X_L+X_C= V^2/Q= 25^2/(-4)=-156.25\Omega$ (1)

(negative Q stands for capacitive VAr)

At 125Hz: $X_F=nX_L+X_C/n=0 \Rightarrow n^2X_L+X_C=0$ (2)

and $\mathbf{n}$=125/50=**2.5**

(2)-(1) gives $\mathbf{X_L}=156.25/(n^2-1)=\mathbf{29.76\ \Omega}$, $\mathbf{X_C}=-n^2X_L=\mathbf{-186.01\ \Omega}$ 13

L=94.74mH, C=17.11μF

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The 50Hz filter current (=4MVA/25kV=160A) is fixed irrespective of train load. 32

However, the filter harmonic current I_F depends on (a) harmonic source current I_S 11 and (b) the main supply Thevenin inductance X_T.
It is called passive filter, since it consists of two passive elements L&C and its harmonic role is passive (harmonic absorption is predetermined by L & C).

The harmonic flows can be easily calculated by 'excel' as follows:

Harmonic current with Filter tuned at 2.5x50=125Hz

pu on 25kV & 26.5MVA base and assumes 4MVA capacitive compensation

X_L=**29.76**x26.5/25²=1.26pu, X_C=-**186.01**x26.5/25²=-7.89pu. (Given: X_T=0.18pu)

				Harmonic number n					
			50Hz	2	3	4	5	6	7
Reactance (pu)	Indcutor	X_L	1.26	2.52	3.79	5.05	6.31	7.57	8.83
	Capacitor	X_C	-7.89	-3.94	-2.63	-1.97	-1.58	-1.31	-1.13
	Filter X_F	X_L+X_C	-6.63	-1.42	**1.16**	3.08	4.73	6.26	7.71
	Tx.	X_T	0.18	0.36	0.54	0.72	0.90	1.08	1.26
Harmonic Current (%)	Filter	I_F		-33.97	31.83	18.97	15.98	14.72	14.05
	Tx.	I_T		133.97	68.17	81.03	84.02	85.28	85.95
	Source I_S	I_F+I_T		100.00	100.00	100.00	100.00	100.00	100.00

At n=3, X_F=**1.16** (positive) and the filter absorbs 32% I_3

At higher n, $X_F=nX_L+X_C/n$ is also positive, and it absorbs 16% I_5, 14% I_7 , ….

But at low n=2, X_F=-1.42pu, I_F absorbs -34%, i.e. I_T is amplified by 34% at Tx

Fortunately, I_2 is very small in ac traction, 34% amplification is of no problem.

Harmonic current with 4-MVA Filter tuned at 2.9x50Hz

32% absorption of the early 125Hz filter is too small (i.e. filter capacity 'wasted')

			55	Harmonic number					
			50Hz	2	3	4	5	6	7
Reactance (pu)	Inductor	X_L	0.89	1.79	2.68	3.58	4.47	5.36	6.26
	Capacitor	X_C	-7.52	-3.76	-2.51	-1.88	-1.50	-1.25	-1.07
	Filter X_F	X_L+X_C	-6.63	-1.97	**0.18**	1.70	2.97	4.11	5.18
	Transf.	X_T	0.18	0.36	0.54	0.72	0.90	1.08	1.26
Harmonic Current (%)	Filter	I_F		-22.34	75.44	29.80	23.28	20.80	19.55
	Transf.	I_T		122.34	24.56	70.20	76.72	79.20	80.45
	Source I_S	I_F+I_T		100.00	100.00	100.00	100.00	100.00	100.00

With closer tuned frequency at 145Hz, X_F is much reduced to **0.18**pu at n=3

The absorption at n≥3 is increased, e.g. 75% I_3, 23% I_5, 20% I_7 … ;
and the amplification at n<3 decreases, e.g. I_{T2} to 22% (previous 34%)

As a conclusion, performances both better than 125Hz filter

Harmonic current with 4MVA Filter tuned at 6.8x50Hz (1)

The train drive also has 7th harmonics, to be absorbed by another 340Hz filter.

				Harmonic number					
			50Hz	2	3	4	5	6	7
Reactance (pu)	Inductor	X_L	0.15	0.29	0.44	0.59	0.73	0.88	1.03
	Capacitor	X_C	-6.77	-3.39	-2.26	-1.69	-1.35	-1.13	-0.97
	Filter X_F	X_L+X_C	-6.63	-3.09	-1.82	-1.11	-0.62	-0.25	0.06
	Transf.	X_T	0.18	0.36	0.54	0.72	0.90	1.08	1.26
Harmonic Current (%)	Filter	I_F		-13.17	-42.26	-186.00	323.84	130.11	95.62
	Transf.	I_T		113.17	142.26	286.00	-223.84	-30.11	4.38
	Source I_S	$I_F + I_T$		100.00	100.00	100.00	100.00	100.00	100.00

This 340Hz filter absorbs 96% I_7, but all lower harmonics are amplified, e.g. I_5 by 124%
Filter may be overloaded with very high I_5=324% of I_S.

Thus, if 7th harmonic filter is to be installed, additional lower harmonic filters may be required. The new 5th harmonic filter will also amplify I_4, I_3, and I_2.

Harmonic current with Filter tuned at 6.8x50Hz (2)

I_5 Resonance occurs if capacitive compensation is reduced from 4 to 2.78MVAr

				Harmonic number					
			50Hz	2	3	4	5	6	7
Reactance (pu)	Inductor	X_L	0.21	0.42	0.63	0.84	1.05	1.26	1.47
	Capacitor	X_C	-9.74	-4.87	-3.25	-2.44	-1.95	-1.62	-1.39
	Filter X_F	X_L+X_C	-9.53	-4.45	-2.62	-1.59	-0.895	-0.36	0.08
	Transf.	X_T	0.18	0.36	0.54	0.72	0.900	1.08	1.26
Harmonic Current (%)	Filter	I_F		-8.80	-26.02	-82.48	18301.4	149.92	93.81
	Transf.	I_T		108.80	126.02	182.48	-18201.4	-49.92	6.19
	Source I_S	I_F+I_T		100.00	100.00	100.00	100.00	100.00	100.00

Controlled 25kV series resonance to absorb more 7th harmonics (94%).

25kV parallel resonance at lower harmonic (I_5 is much amplified)

Harmonic current with Filter tuned at 6.8x50Hz (3)

I_3 Resonance occurs if capacitive compensation is increased to 13.5MVAr 54

				Harmonic number						
			50Hz	2	3	4	5	6	7
Reactance (pu)	Inductor	X_L	0.04	0.09	0.13	0.17	0.22	0.26	0.30
	Capacitor	X_C	-2.01	-1.00	-0.67	-0.50	-0.40	-0.33	-0.29
	Filter X_F	X_L+X_C	-1.96	-0.92	-0.539	-0.33	-0.18	-0.07	0.02
	Transf.	X_T	0.18	0.36	0.540	0.72	0.90	1.08	1.26
Harmonic Current (%)	Filter	I_F		-64.70	38971.1	183.69	125.75	107.36	98.66
	Transf.	I_T		164.70	-38871.1	-83.69	-25.75	-7.36	1.34
	Source I_S	I_F+I_T		100.00	100.00	100.00	100.00	100.00	100.00

Controlled series resonance to absorb more 7th harmonics (99%).

Parallel resonance at lower harmonic (I_3 is much amplified)

Harmonic current with Filter tuned at 4.8x50=240Hz

I_3 Resonance occurs if capacitive compensation is increased to 10MVAr

				Harmonic number						
			50Hz	2	3	4	5	6	7
Reactance (pu)	Inductor	X_L	0.12	0.24	0.36	0.48	0.60	0.72	0.84
	Capacitor	X_C	-2.77	-1.39	-0.92	-0.69	-0.55	-0.46	-0.40
	Filter X_F	X_L+X_C	-2.65	-1.14	-0.563	-0.21	0.05	0.26	0.45
	Transf.	X_T	0.18	0.36	0.540	0.72	0.90	1.08	1.26
Harmonic Current (%)	Filter	I_F		-45.88	-2378.42	141.63	95.02	80.61	73.86
	Transf.	I_T		145.88	2478.42	-41.63	4.98	19.39	26.14
	Source I_S	I_F+I_T		100.00	100.00	100.00	100.00	100.00	100.00

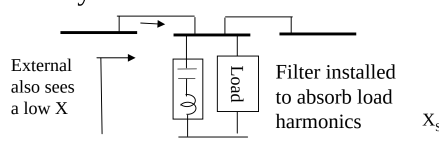
Controlled series resonance to absorb more fifth harmonics (95%).

Parallel resonance at lower harmonic (I_3 is much amplified)

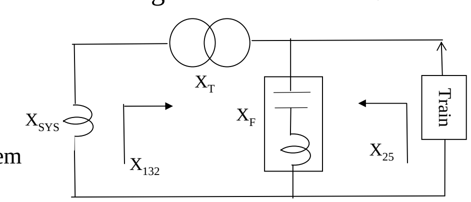
Higher-order and multi-leg filters have potential resonant hazard.

'Problems' of 3rd harmonic filter design in East Rail

Power system is rich in 3rd harmonics but the magnitude is unknown.



Filter and consumer load connected to system (filter also absorbs external harmonics)



21

Possibly with fear of 'resonance', early filters in KCR tuned **not** closed to 150Hz had restricted the absorbing capacity of passive filter (32%). 13

Resonance may be due to very low X_{25} and/or X_{132}, overloading the filter.

If the 3rd harmonic filter is tuned closed to 150Hz, say at 145Hz,

X_T=0.54 at 150Hz is slightly increased and is positive 14

X_F=0.18 is much reduced but remains also positive

X_{25} ($\approx X_T // X_F \approx X_F$) is small, series 'resonant' design to increase absorption to 75%.

(Filter rating is determined by the foreseeable total max train harmonic current I_S.) 40

X_{132} ($\approx X_T + X_F \approx X_T$) is always large, irrespective of X_F. 13

150Hz resonant at 132kV PCC due to 3rd harmonic filer is impossible. 20

Resonance at other frequencies

Recall X_T=0.18pu at 50Hz, and $X_{132} \approx X_T+X_F$ for all frequencies

- At 150Hz, both X_T & X_F are positive, no resonance
- Above 150Hz, both X_T & X_F are more positive, no resonance

19 $X_{132} \approx X_T+X_F$ 14

- At 50Hz, X_T=0.18pu. System may resonant if $X_F \approx$-0.18pu, i.e. if capacitive compensation is 26.5/0.18=147MVAr
- At 100Hz, system may resonant if the capacitive compensation is 22MVAr 21

$X_{25} \approx X_T // X_F$ 19

- The maximum capacitive compensation in KCRC is 4MVAr.

Conclusion :

Resonance (series or parallel) due to 145Hz filter is impossible.

Heavy 3rd harmonics in East Rail can be combated by tuning filter closed to 150Hz, with adequate filter rating. 22

Harmonic current (Filter tuned at 2.9x50Hz and with **22**MVAr compensation)

				Harmonic number						
			50Hz	2	3	4	5	6	7
Reactance (pu)	Inductor	X_L	0.16	0.33	0.49	0.65	0.81	0.98	1.14
	Capacitor	X_C	-1.37	-0.68	-0.46	-0.34	-0.27	-0.23	-0.20
	Filter X_F	X_L+X_C	-1.20	-0.358	0.03	0.31	0.54	0.75	0.94
	Transf.	X_T	0.18	0.360	0.54	0.72	0.90	1.08	1.26
Harmonic Current (%)	Filter	I_F		23041.7	94.41	70.01	62.53	59.10	57.21
	Transf.	I_T		-22941.7	5.59	29.99	37.47	40.90	42.79
	Source I_S	I_F+I_T		100.00	100.00	100.00	100.00	100.00	100.00

Controlled 25kV series resonance to absorb more third harmonics (94%)

25kV parallel resonance and I_2 is much amplified (where $X_{25} \approx X_T // X_F$)

Uncontrolled 132kV series resonance according to $X_{132} \approx X_T + X_F$ 19 and external (132kV) I_3 magnitude is unknown.

20

Harmonic Problems in West Rail

Characteristics of new drive of SP1900 (IKK) train

- Unity power factor
- Rich in low harmonics with some high-order harmonics
- Passive filter (causing over-compensation and overvoltage at 50Hz) is inappropriate for installation. 49

In a consultancy study of including IKK train in the East Rail (one IKK with 4 convention MLR), for a scenario of the only IKK train in powering mode:

- poor and negative power factor = -0.427,
- over-compensation by 3MVAr and **over-voltage** (V=1.073pu)

Other Problems:

High-order (over 50[th]) harmonics generated by unity pf drives

Passive filter tuned at, say, n=50.5 must amplify harmonics h<n, and may lead to resonance at some lower h's.

Passive filter cannot be installed to the West Rail.

Possible solution: Active Filter directly connected to at 25kV ? 50

(Present G4/5 regulation only covers h<51.)

Standard for Harmonics

	Harmonic	2	3	4	5	6	7	8	9	10	11	12	13	THD
G5/3	Current (A)	5	4	3	4	2	3	1	1	1	3	1	3	
G5/4	Voltage (%)	1	2	0.8	2	0.5	2	0.4	1	0.4	1.5	0.2	1.5	5%

Total harmonic distortion (THD) on voltage

G5/3: $V_T = \sqrt{\sum_2^{\infty} V_n^2} < 1.5\%$ "sufficient to use values of up to 19"

G5/4: $V_T = \sqrt{\sum_2^{50} V_n^2} < 5\%$ n>50 is ignored in THD calculation

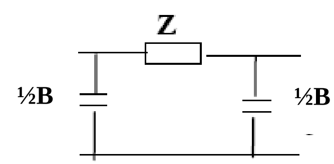
Necessity to revise existing regulation ?

High-order harmonics recorded beyond PCC

High order harmonic current were recorded at 132kV s/s beyond PCCs supplying West Rail and also East Rail.

These s/s are connected to PCC via 132kV cables.

A cable represented by π-equivalent has 3 parameters: R, L & C, where **Z**=R+jX, X=ωL and B=ωC at 50 Hz

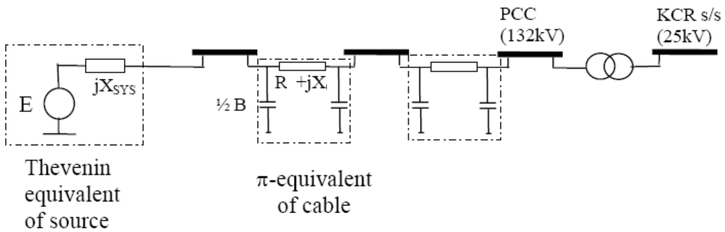


π equivalent of Cable

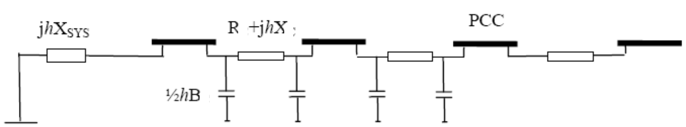
For h^{th} harmonic, $\mathbf{Z}_h \approx R + jhX$, and $B_h = hB$.
Both $\mathbf{Z}_h$ and B_h will increase with *h* and cable length.

The 50Hz charging current V^2B is very high at V=132kV.

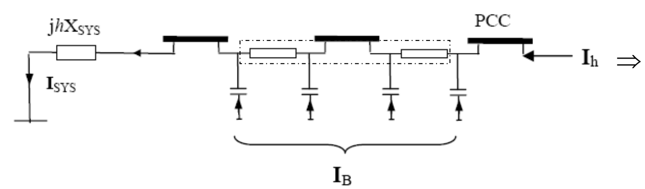
System modeling at 50Hz

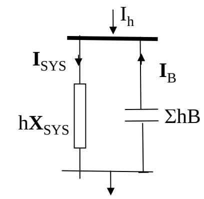


System modeling at h harmonic



Harmonic current flows at 132kV





Appro. equivalent circuit at s/s if $Z_h \approx 0$

I_h (small) from traction is injected to 132kV system via PCC, and will return via I_{sys} (positive) and I_B (negative)

I_{SYS} at a s/s is much amplified if $hX_{SYS} \approx 1/h\Sigma B$ (parallel resonance)

54

To meet $hX_{SYS} \approx 1/h\Sigma B$, the location of resonance (ΣB), the harmonic order (h), and the time in a day (X_{SYS}) can vary. Fortunately, many R's in the two Z branches and connected loads will attenuate current amplification in parallel resonance, if any.

Note the approximate equivalent circuit does not include 25kV (i.e. not related to filter design), and this 132kV resonance may not be detected in KCR.

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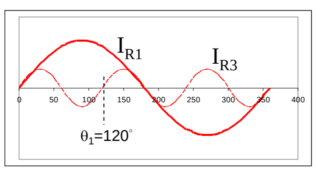
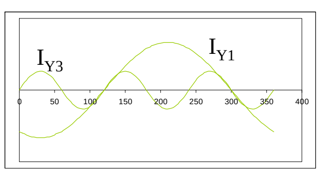
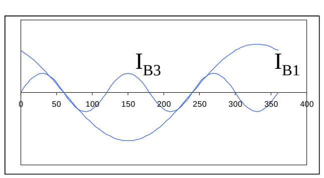
Effect of 3rd harmonic current in neutral wire for 3-phase

Harmonics in 3-ph system:







$\theta_1=\omega t$ for fundamental, $\theta_n=n\omega t$ for n^{th} harmonic
For the same time span t, $\theta_n=n\theta_1$
When 3th harmonics completes one cycle, the fundamental goes through only 120°

Under balanced load, the neural wire current $I_N=I_R+I_Y+I_B=0$ for fundamental 50Hz
But, their 3rd harmonics are in-phase
$I_{R3}=I_{Y3}=I_{B3}$ and $I_{N3}=3I_{R3}$
This also applies to harmonics of 6th, 9th, ….

If a system has, say, 40% 3rd harmonic,
let $I_1=1$, $I_P=\sqrt{(1^2+0.4^2)}=1.077$, $I_N=3\times0.4=1.2$,
$I_N>I_P$ and the neutral wire may be overloaded.

I_3 (%)	0	10	20	30	40	50
I_P	1.000	1.005	1.020	1.044	1.077	1.118
I_N	0	0.3	0.6	0.9	1.2	1.5

Harmonic in Automated People Mover (APM) System for Airport

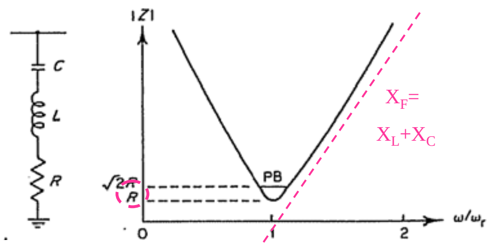
- The 3-ph 600V supply to APM does not have neutral wire, and I_3 is suppressed.
- Harmonics of 5, 7 &11 are rich and 3-leg filters were already installed.

- Whilst I_5 is absorbed by 5th harmonic filter (<100%), it is amplified by 7th harmonic filter.
- Similarly, 11th harmonic filter must amplify I_5 and I_7.
- Resonance may occur at I_5 and I_7. 16

- Multi-leg filter may not be effective to absorb multi harmonics.
- A solution is to install only 5th harmonic filter to absorb I_5, as well as I_7 and I_{11} (but with larger filter rating). 14
- Alternately method: install active filter, since V is low (600V) 50

Traditional Concept on Singly tuned Filter

Why engineers do not aware lower harmonic amplification in mulit-leg filter?



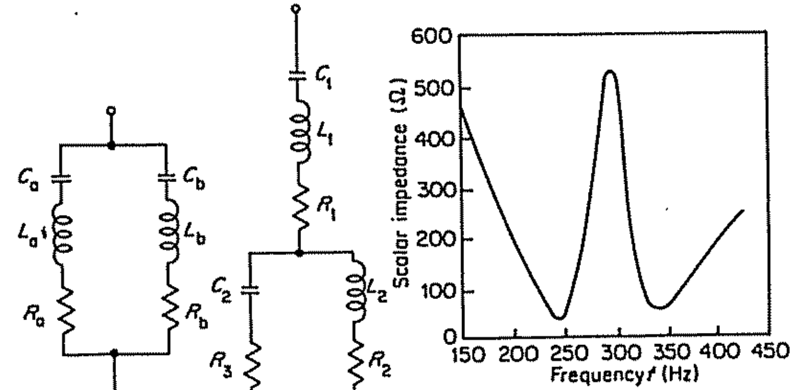
The filter impedance is $\mathbf{Z}=R+j(\omega L-1/\omega C)$ and $|Z|=\sqrt{\{R^2+(\omega L-1/\omega C)^2\}}$ is <u>always</u> positive

At tuned frequency ω_r, $\omega_r L=1/\omega_r C$, and $|Z|=R$ 31

The filter has the lowest $|Z|=R$ (i.e. highest absorption) at ω_r. However, this tuning concept may be adequate to the filter design at power system, but inadequate at traction substation which has a 132/25kV Tx in parallel with the filter.

The absorption concept at $\omega>\omega_r$ also applies, but this concept has overlook that negative reactance X at $\omega<\omega_r$ will amplify the low-order harmonic flows in the Tx.

Traditional Concept on Double tuned Filter



Characteristic of a 2-leg filter (5^{th} and 7^{th})

Similar inadequacy of using scalar impedance $|\mathbf{Z}|$ also occurs on double tuned filter, e.g. 2-leg filter.

Discrepancy of Traditional Concept

Filter impedance $\mathbf{Z}$=R+jX is a complex number, a 2-D vector.

To fully depict $\mathbf{Z}$ variation with frequency f, a 3-D graphic is necessary. But 3-D analysis is complicated and difficult.

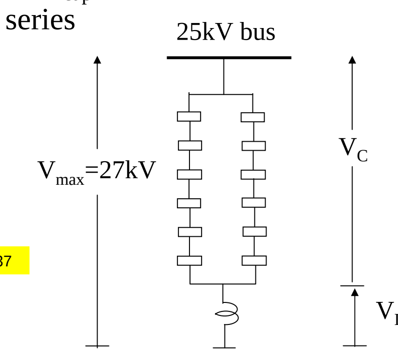
To depict $\mathbf{Z}$-f relationship by 2-D, traditional concepts use 1-D of Z=|$\mathbf{Z}$|, but the abrupt sign change of X is overlook. 29

In the present presentation, the small R is ignored and $\mathbf{Z}\approx jX$ is simplified to 1-D.
Finally the $\mathbf{Z}$-f relationship becomes a 2-D problem. 11
The advantage is that the abrupt sign change of X and the harmonic current absorption/amplification can be estimated using simple excel program.

Another common error in filter design

With passive filter, the 50Hz capacity compensation will be excess when less train at powering mode and may lead to over-compensation and over-voltage. The max. allowable voltage for KCR ac traction drive is 27.5kV. 12

Suppose each cap has a voltage rating of V_{cap}=4.5kV.
For V_{max}=27kV, the number of cap in series appears to be $s=V_{max}/V_{cap}=27/4.5=6$



However, the actual voltage across the cap is $V_C>V_{max}$ since V_C and V_L are of opposite sign 52

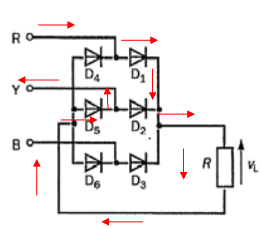
It should be $s=V_{max}/V_{cap}+X_L\omega Cp$ 37

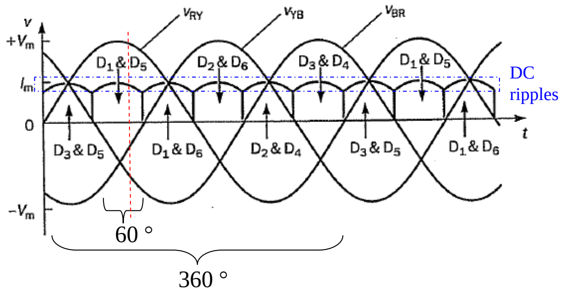
(Details to be provided in EE510)

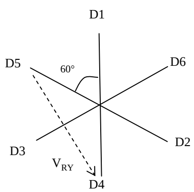
Filter design based on $s=V_{max}/V_{cap}$ may lead to capacitor insulation failure under higher voltage stress.

Harmonics in dc traction system

In 3-ph system, DC supply obtained from full wave rectifier is common.



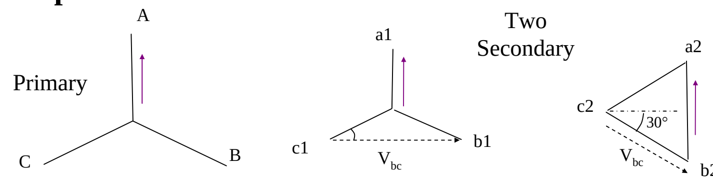




The DC output voltage has six 'sections' in one cycle (i.e. the so-called 6-pulse rectifier), and each section is of 360/6=60°.

DC ripple can be reduced by more pulse rectifiers

12-pulse Rectifier



If a 3-ph Tx has two sets of secondary windings of star and delta connections, the secondary line voltages will have an angle difference of 30°.

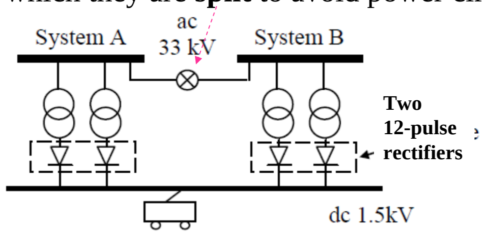
If a rectifier is fed by these two secondary windings, the rectifier output V_{DC} will be of 360/30=12 pulses, and the DC ripple is smaller than that of the 6-pulse rectifier.

For 12-pulse rectifier, harmonic current I_h with h=12k±1 (i.e. 11,13, 23, 25, 35, 37…) will exist at the Tx primary, and I_h/I_1=1/h is simply the reciprocal of h which is rather small at high h values.
(I_1 is the fundamental 50Hz Tx current.)

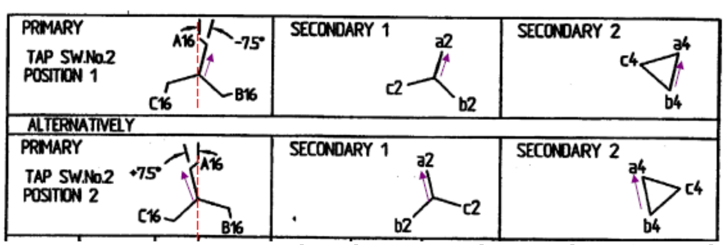
In 24-pulse rectifier, I_h for h= 11, 13, 35 & 37 are further suppressed.

24-pulse rectifier in DC traction system

In MTR, the each 1.5kV source is a pair of Tx rectifier of 12-pulse each. These Tx are connected to 33kV systems (of both CLP and HEC), in which they are **split** to avoid power circulation.



Each Tx has zig-zag primary winding, such that one Tx winding of –7.5° phase shift and the other +7.5° (by means of phase shift change switch), i.e. an angle difference of 15 °



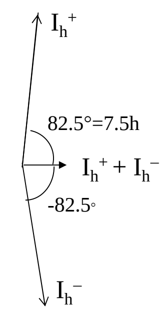
Then V_{DC} will be of 360/15 =24 pulse.

Each Tx has 2 secondary windings (star and delta).

Harmonic suppression by 24-pulse rectifier

The two primary current have an angle difference $\Delta\theta_1$=7.5-(-7.5)= 15° at 50Hz, and $\Delta\theta_h$=7.5h-(-7.5h)=15h° at harmonic frequency, given by:

h	11	13	23	25	35	37
15h	165	195	345 (-15)	375 (15)	525 (165)	555 (195)
∣RF∣	0.13	0.13	0.99	0.99	0.13	0.13



Current sum of 2 Tx for h=11

For h=11, 7.5×h=82.5°, 82.5°×2=165°

Reduction factor (RF)

RF = cos82.5°=0.13, and similarly for h=13, 35 & 37.

Thus, only 23th and 25th harmonics can only be rich in the 24-pulse rectifier with magnitude I_h/I_1=1/h.

In MTR, the high harmonic injection to PCC is very unlikely, but the hazard of harmonic resonance beyond PCC for all h (due to B of 33kV cable & 33kV cap) still exists.

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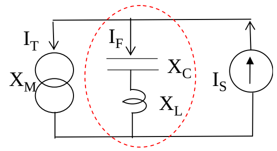
Summary of major observations

Two types of resonance associated with ac traction harmonic at 25kV are:

At series resonance,

$-X_L \approx X_C$ and max $I_F = I_S$, $|V_C + V_L|$ is much smaller than $|V_C|$ or $|V_L|$, implying voltage resonance. 55

However, as train harmonic I_S is foreseeable, voltage resonance is 'controllable' by tuning at n (where n<h), and the amount of filter absorption of I_F can be controlled.



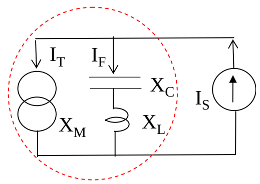
So long taking $s = V_{max}/V_{cap} + XL\omega Cp$ in the filter design, equipment insulation failure due to voltage resonance should not occur. 32

At parallel resonance,

$-X_M \approx X_C + X_L$, and $I_F >> I_S$ (can be > 100) $\Rightarrow$ current resonance

Both V_L & V_C can be of large values $\Rightarrow$ voltage resonance

Since X_M consists of Tx and 132kV system circuits as well as fault level, when will this resonance occur is uncertain.



From analyses, parallel resonance should not occur for 3th harmonic filter, even 50n is tuned close to 150Hz (to increase absorption), but not for filter of harmonics 5th, 7th .., nor for multi-leg filter.

132kV series resonant (slide-21) and parallel resonances (slide-26) are all 'uncontrollable'.

Comments on harmonic impact on the 4 local railway systems (1)

1. East Rail (25kV 1-ph)

Mainly low order harmonics and h=3 dominant. The problem can be solved with passive filter tuned closed to 150Hz and with proper filter rating according to foreseeable total harmonic current I_S. Harmonics issues becomes complicated with IKK (trains of unity power factor) that over-compensation and over voltage will occur, but the advantage is that 3rd and 5th harmonics from IKK will be anti-phase to (i.e. cancel) those from conventional train. Capacitors will likely experience overvoltage due to over-compensation and inadequate capacitor design of $s = V_{max}/V_{cap}$.

2. West Rail (25kV 1-ph)

Because of the unity power factor drive of IKK, both low- and high-order harmonics exist. With the conflicts of (a) over-compensation and over-voltage and (b) low harmonic amplification (or even resonance), passive filter cannot be installed. Since the technique of HV active filter is not yet mature, no pragmatic measures can be recommended.

Comments on harmonic impact on the 4 local railway systems (2)

3. Automated People Mover (600V 3-ph)

Rich in low-order harmonic with the absence of 3 and 3-multiples. Multi-leg filter (5, 7 & 11) has been installed, and lower order harmonics must be amplified. A proper filter design has to look after the filter loading increase due to lower harmonic amplifications, and to avoid the hazard of 5th and 7th harmonic resonances.

4. Mass Transit Rail (1.5kV DC)

Mainly h=23 & 25 with magnitude of I_1/h. Magnitudes of h=11, 13, 35 & 37 are further reduced to 13% of I_1/h by the 24-pulse rectifier Tx. Very heavy harmonic injection to PCC should not occur.

In all above 4 cases, there is a potential hazard of parallel resonance beyond PCC, even the traction harmonic injection is small. If it really happens, the role of responsibility should be the supply utility, not MTRC.

END of Presentation

Q & A

The excel program for the harmonic calculations, the PDF files (colored) of the present slides on traction harmonics and the previous slides on traction Imbalance can be downloaded from:

ftp://ftp.ee.polyu.edu.hk/cttse/seminar 1

Animations by Icons: e.g.

11 Go to slide-11

12 Return to slide-12

Annex-1

Power Quality equipments in EE Power systems Lab

Installed at EE in 2003 with full support from ABB (HK)

Except the 2 motors, all the PQ equipments and supply panels (MINIC/MNS) are freely designed/transported/installed by ABB(HK) for EE Dept of PolyU for teaching/research purposes.

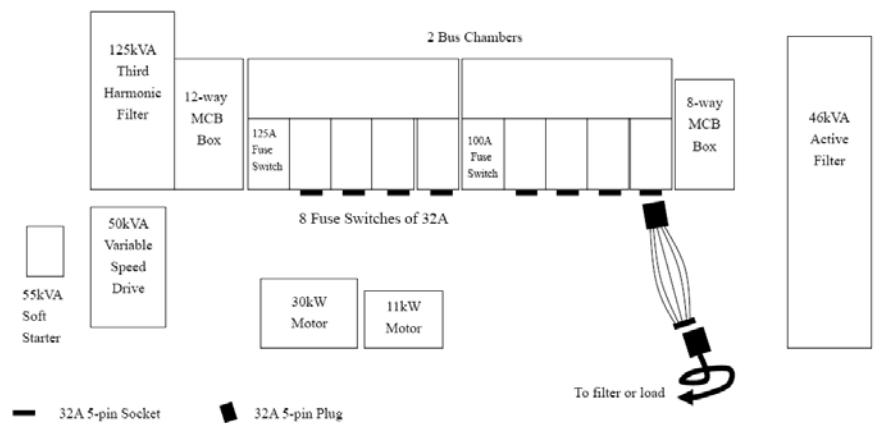
MINIC & MNS: Power Supply to PQ and other labs

Overall view of PQ equipments

44

Power Quality Analysis Equipment

A Project Fully Supported by ABB (HK)



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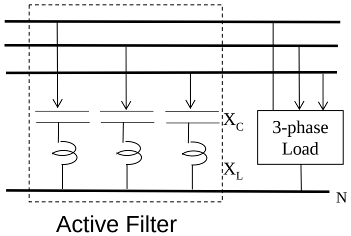
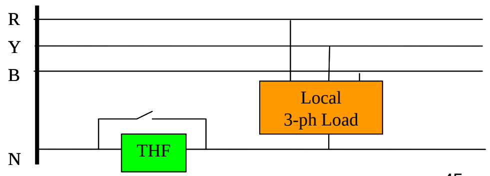
Active Filter
(in parallel with load)

Third Harmonic Filter THF
(at neutral & in series with load)





Motors & Drives

30kW & 11kW motors

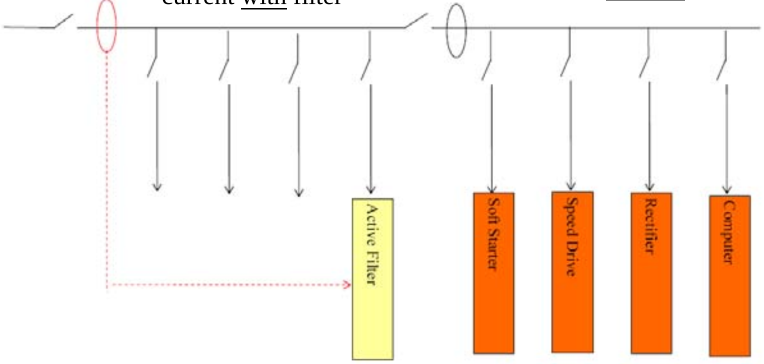
Inverter or Variable speed drive, driving 30kW motor

Soft starter driving 11kW motor

Performance Test of Active Filter

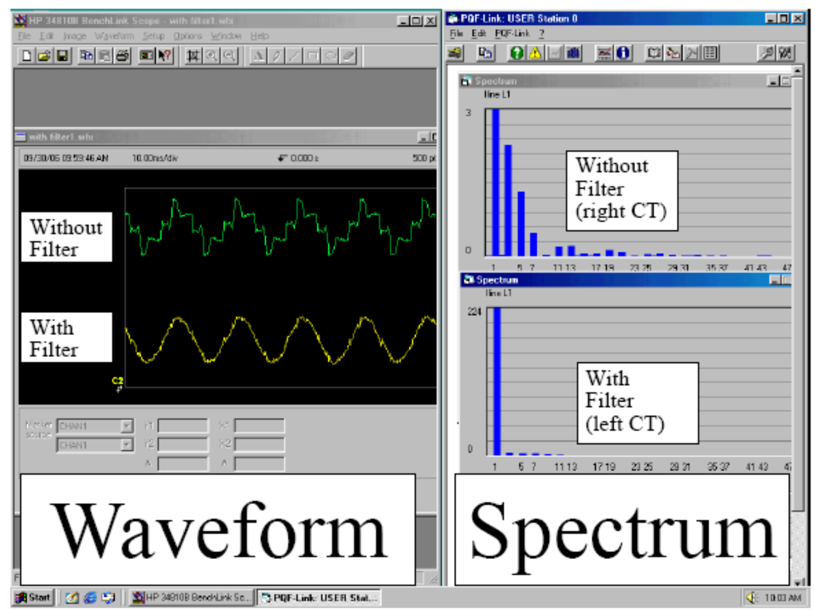
CT-1 measures total current with filter

CT-2 measures total load current without filter



- The Active Filter senses the current via the current transformer (CT-1)
  On-line computes the measured harmonic current: magnitude and angle
- AF injects harmonic current (equal but opposite to local harmonics) until TOTAL harmonic current of CT-1 reach specified values

Effect of Active filter



Annex-2

Traction Harmonics and Research on Active Filter

Problem with trains of unity/leading power factor

- A proper filter design has to look after both the capacitive compensation at 50Hz and the anticipated total harmonic current for all foreseeable scenarios.
- A passive filter will absorb harmonics generated by trains, but it will inevitably generate MVAr to be absorbed by train load.
- The shortcoming of trains with unity power factor is the incapability to absorb MVAr, resulting in system over-compensation and over-voltage.
- Thus, unity power factor may not be beneficial to a system if a passive filter has to be installed.

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Necessity of Active Filter

With advance of Power Electronics, more rich in high order and multi order harmonics

Advantages:

Without lower harmonic amplification nor resonance

Programmable capability to handle dynamic range of harmonics

Immune to external harmonics

Applicable to lagging/unity/leading power factor load

Restrictions of existing Active Filter design

Harmonic order below h=50

Voltage below 1 kV

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Proposed Research Proposal of more advanced Active Filter

- Higher voltage level (11kV and then 25kV)
- Faster dynamic response to combat the high order harmonics.
- Optimal selections and design of the power electronic converters and the coupling transformer
- Suitable operational voltage to improve efficiency and improve response
- Can handle both single-phase and three-phase applications
- Can handle shallow voltage dip of short durations (say less than 200ms) in low power installations.

Annex-3**: Revision on Circuit Theory**

By ohm's Law

$I \propto V$, i.e. V=RI or I=GV for DC

R: resistance, G: conductance (=1/R)

For AC: V=ZI or I=YV

Z=R+jX (impedance), Y=G+jB (admittance)

(X is reactance, B is susceptance)

For purely reactive element, R=0 or G=0

Z=jX, Y=jB

For the same element

$Y=1/Z \Rightarrow jB=1/jX \Rightarrow B= -1/X$ (B & X of opposite sign)

Inductor: $Z_L = jX_L = j\omega L$ or $Y_L = jB_L$ (B_L is negative)

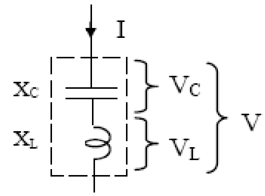
Capacitor: $Y_C = jB_C = j\omega C$ or $Z_C = jX_C$ (X_C is negative)

Simple Circuit Analyses

Series circuit: more convenient to use $Z=Z_1+Z_2+\ldots$
Parallel circuit: more convenient to use $Y=Y_1+Y_2+\ldots$

Series circuit of inductor and capacitor

Total $X=X_L+X_C=\omega L+(-1/\omega C)$



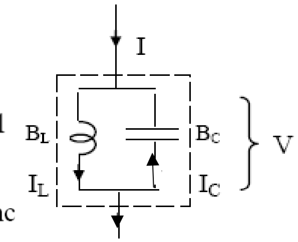
Resonance occurs when total $X\approx 0$, i.e. when $\omega^2 LC\approx 1$

If a current I is injected to the series circuit at resonance,
voltage $V=IX$ is small,
but $V_L=IX_L$ and $V_C=IX_C$ (of opposite sign) can be large (if X_L or X_C is large.)

but X_L and X_C values at resonant freq ω are finite,
and resonant V magnitude is restrictive.

Parallel circuit of inductor and capacitor

Total $B=B_L+B_C=(-1/\omega L)+\omega C$



Resonance occurs when total $B\approx 0$, i.e. when $\omega^2 LC\approx 1$

If a voltage V is applied to the parallel circuit at resonanc
current $I=VB$ is small,
but $I_L=VB_L$ and $I_C=VB_C$ (of opposite sign) can be large.

At 50Hz, power system has V source.
At resonant ω, however, the system has no V source
Harmonic current injection is more appropriate

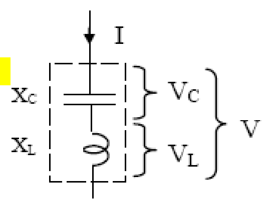
Thus, for an external current I injection,
the internal I_L and I_C (of opposite sign) can be large
and $V=I_LX_L=I_CX_C$ can be large.

In general, parallel resonance (with both V and I) is more severe than series resonance (with V only), due to the possibly large internal current.

Example of series circuit for 2.9×50=145Hz Filter

Base values: S_b=26.5MVA, V_b=25kV, $I_b=S_b/V_b$=1.06kA,

At 50Hz, X_{L1}=0.89pu, X_{C1}=-7.52pu, V_1=25kV (i.e. 1pu)
$V_{L1}=X_{L1}/(X_{L1}+X_{C1})V_1$ = -0.134pu (-3.35kV),
$V_{C1}=X_{C1}/(X_{L1}+X_{C1})V_1$ = 1.134pu (28.35kV)
(subscript 1 stands for 50Hz fundamental)



At 150Hz, $X_{L3}=3X_{L1}$=2.68pu, $X_{C3}=X_{C1}/3$=-2.51pu,
and close to resonance
For injection of even a very large I_3=10A (i.e. 0.00943pu)

$V_{L3}=I_3X_{L3}$= 0.025pu,
$V_{C3}=I_3X_{C3}$=-0.023pu

Adverse effect due to series resonance is marginal with foreseeable I_3

Total $V_L=\sqrt{(V_{L1}^2+V_{L3}^2)}$ = 0.136pu, (3.4kV)
total $V_C=\sqrt{(V_{C1}^2+V_{C3}^2)}$ = 1.134pu (28.35kV)

Only slight increase from V_{L1} & V_{C1}

By proper design of the voltage and current ratings for both L & C,
this 145Hz filter should be effective to absorb 3rd harmonic current.

Biography of Speaker

- Dr. C.T. Tse was the Associate Professor in the Electrical Engineering Department, the Hong Kong Polytechnic University (PolyU).
- Before joining the Hong Kong Polytechnic in 1990, Mr. Tse was the Planning Engineer of System Planning Branch in CLP. His main duty was to look after power system stability and the ‘abnormal’ loads, such as arc furnace and traction.
- During his 20-year service in PolyU, Dr. Tse has engaged in 7 consultancy investigations associated traction power supply (3 with KCR, 2 with MTR, one with KCR/MTR and one with an overseas 1.5kV DC project). One of his research works was supported by MTRCL via the PolyU Teaching Company Scheme in 1996
- As the Visiting Associate Professor with the EE Dept after retirement since September 2010, three of his taught MSc subjects (EE510, EE533 & EE537) related with traction systems are continued.

IEEE/HKIE Seminar

Impact of Imbalance of Single-Phase Traction to Three-Phase Power System

Delivered by Dr C T Tse

Nov-7, 2010 (Tue)

N003, PolyU

Contents

Brief History of 25kV Railway Electrification in HK

1981: Commissioning of Tai Wai KCR s/s, the new ERL was supplied by two Tx: TWN and TWS. 17

1989: Commissioning of Fanling KCR s/s with two Tx: FLN and FNS. ERL power was then supplied by four Tx in two s/s. 5

2003: Commissioning of Tin Shui Wai WR s/s, supplying power to the new WRL.
2003: Commissioning of Kwai Fong WR s/s, WRL power was then supplied by four Tx in two s/s.
2004: Commissioning of Ho Man Tin KCR s/s, HMTN replaced TWS, and TWS was then at standby. ERL power was then supplied by four Tx at three s/s.
2004: ERL was extended to East Tsim Sha Tsui (ETS), power supplied by HMTS. ERL power was then supplied by five Tx in three s/s.
2005: Commissioning of new MOL, power was supplied by one Tx of MOS. 23
2009: KSL was completed and ETS extension became part of WRL. Since then, WRL power was supplied by five Tx in three s/s, and ERL by four Tx in three s/s.

For simplicity, installation of standby Tx at Wu Kai Sha s/s (for MOL), Kwai Fong WR s/s, Tin Shui Wai WR s/s and Fanling KCR s/s are skipped in the above brief history. (Including TWS, total **5** standby Tx in KCR.) 40

Different traction supplies for Metro Lines

Operating voltages in dc and ac systems

		DC	AC
Nominal voltage (kV)		1.5	25
Minimum voltage (kV)		1.2	17.5
Lower limit dVL	(kV)	0.3	7.5
	(%)	20	30

Voltage dip $dV \approx ZI = Z(S/V)$

per unit dV is $dV/V \approx ZS/V^2$, where Z=conductor impedance

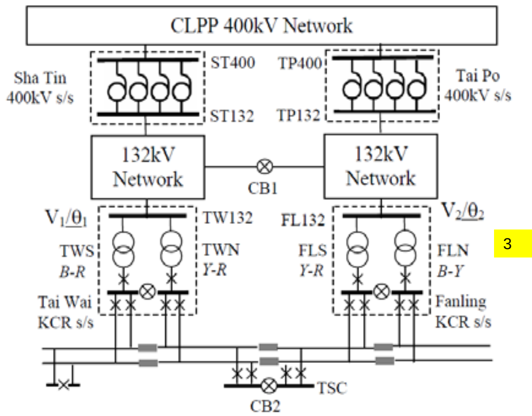
For the same train load S, and using similar conductor,

$dV_{ac}/dV_{dc} \approx (1.5/25)^2 = 0.06^2 = 0.0036$

Consequently, ac system has a much smaller dV, but can operate within wider dVL. In system design, less number of infeed s/s is required for a 25kV ac system versus dc system, and therefore 25kV system is widely adopted for intercity train service over long distance (i.e. to allow larger total Z) and more trains (i.e. larger S).

Merit of AC Traction System

- For instance, in 1994, the MTR (with a total length of 35km) has 18 s/s in three urban lines and the KCR (with a total length of 34km) has only 2 infeed s/s.
- The rail lengths per substation are 1.9km for MTR and 17km for KCR (8.8 times of MTR).



KCR system in 90'

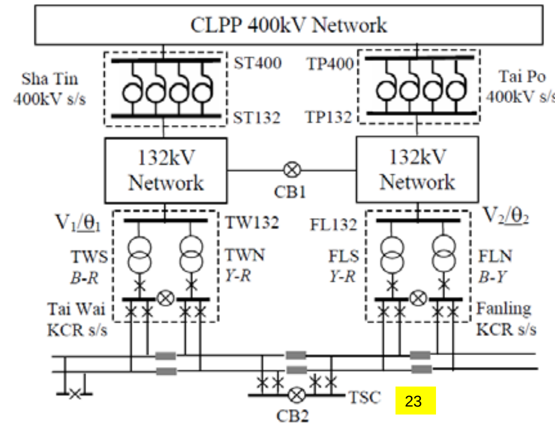
(For clarity, MTR and KCR here are merely used to distinguish the two types of electrified metro transit system in HK, both now under MTRCL.)

Weakness of AC Traction System

In 90's, KCR had 4 sections, with 4 single-ph Tx with 3 different phases.

The 132kV network has to be split by CB1 due to fault level problem. (Maximum fault level only allows 6 parallel 400/132 kV auto-Tx).

In ac system, MW flow ΔP between two buses is proportional to the angle difference Δθ, but θ cannot be controlled. (MVAr can be controlled by Tx tap.)



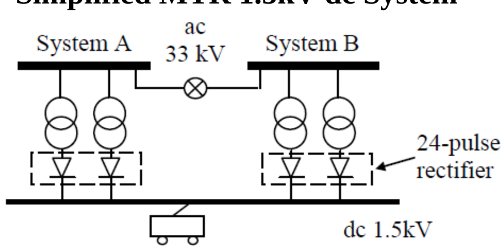
If CB2 is closed, the 3-ph power may flow from ST400 to TP400 via the 1-ph 25kV KCR, which is strictly prohibited.

Therefore, each subsystem in KCR can only be supplied by *only one* 132/25 kV Tx.

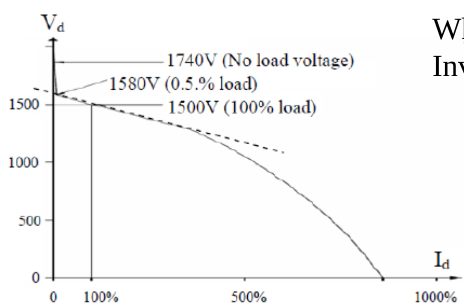
Should any Tx failure occur, all trains connected to that section will temporarily lose supply, until power supply is restored from an adjacent (or standby) Tx.

Power Flow in DC Traction System

Simplified MTR 1.5kV dc System



The 3-ph 33kV ac distribution systems of MTRCL are split by ⊗ to avoid power circulation via 33kV ac.



V-I characteristic of 4MW Rectifier

When supplying load, V_d <1580kV; Inversion only operates at V_d>1740V

In dc system, power flow is from HV bus to LV bus

So long the rectifier characteristics are identical, there is no power circulation problem via dc system.

Merit of DC Traction System

In MTR dc system, all the 1.5kV rectifier outputs can be coupled and every train will be supplied by multi rectifier sources.

In case of one or several Tx failure, the train service is not disturbed.

Relative Merits of AC and DC systems

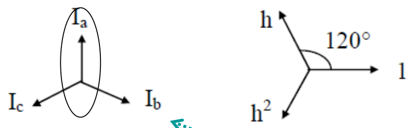
In terms of voltage dip, ac system is preferred.
In terms of supply security, dc system is much better.

Subsequent analyses will be focused on single-phase ac traction system supplied by 3-phase power system.

For 1-phase train load, imbalance to 3-ph supply is inevitable. The analytical technique is by means of sequence component.

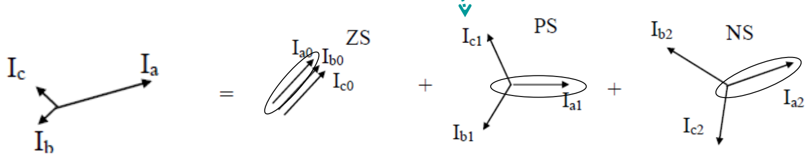
Analysis of Unbalance 3-phase Load by Sequence Component

Balanced 3-ph load



h=/120° operator and $1+h+h^2=0$

In a balanced 3-ph system, there is only one independent current phasor, say, I_a, because $I_b=h^2Ia$ and $I_c=hI_a$.



However, in the unbalanced case, all the 3 current phasors are required. 10

For balanced system, components of zero sequence (ZS) and negative sequence (NS) are null, and only positive sequence (PS) exists.

Symmetric Components

Suppose these phasors can be decomposed into symmetric components, namely, zero-, positive-, and negative- sequences:

Subscript 'a' is dropped for simplicity

$$I_a = I_{a0} + I_{a1} + I_{a2} = I_0 + I_1 + I_2$$
$$I_b = I_{b0} + I_{b1} + I_{b2} = I_0 + h^2 I_1 + hI_2$$
$$I_c = I_{c0} + I_{c1} + I_{c2} = I_0 + h I_1 + h^2 I_2$$

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In matrix form:

$$\begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & h^2 & h \\ 1 & h & h^2 \end{bmatrix} \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix}$$

In short, $\mathbf{I_p}=\mathbf{TI_s}$ and similarly $\mathbf{V_p}=\mathbf{TV_s}$

The inverse is:

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \tfrac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & h & h^2 \\ 1 & h^2 & h \end{bmatrix} \begin{bmatrix} I_a \\ I_b \\ I_c \end{bmatrix}$$

In short, $\mathbf{I_s}= \mathbf{T^{-1}} \mathbf{I_p}$ and similarly $\mathbf{V_s}= \mathbf{T^{-1}} \mathbf{V_p}$

Therefore, given any phase vector $\mathbf{I_p}$, the sequence vector $\mathbf{I_s}$ can be evaluated.

As a result, instead of representing by three *phase* values, the current can be expressed by three *sequence* values. 9

One of the advantages of sequenty component representation is to provide a measure of imbalance, e.g. I_2/I_1 or I_1/I_1.

(Supply rule 2000 from CLP website)

Type of Distortion	Type of Abnormal Load	Operational Limit
Voltage Fluctuation	Electric arc furnace	• for 132kV and below 2 %
	Motor starting	• Infrequent (intervals exceeding 2 hours) 3 % • Frequent (intervals not exceeding 2 hours) 1 %
	Rolling mill and traction (motor starting intervals not exceeding several minutes)	• Step-type change : up to 66kV 1 % 132kV ¾ % • Ramp-type change : up to 66kV 1 % /sec 132kV ¾ % /sec • Limit of total change : up to 66kV 3 % 132kV 2½ %
Voltage Unbalance	Single phase electric traction load	• Voltage : negative sequence 2 % of positive sequence • Current into generators : negative sequence 5 % of positive sequence

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Voltage Imbalance V_2 at point of common coupling

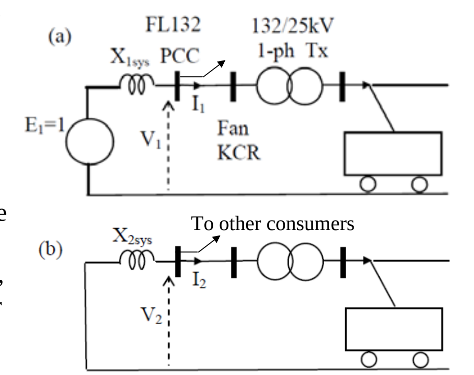
Only V_2 will affect the supply Power Quality of other consumers, not I_2.

For many years, CLPP has regularly monitored V_2 at PCC

If a 132kV s/s is fed by six 400/132 kV auto-Tx, the fault level is close to the CB rating of 7200MVA (or 7200/26.5 =272pu on Tx 26.5MVA base)

Thus, the fault level of FL132 (fed by 4 auto-Tx) is about 272×4/6=181pu.
X_{1sys}=1/181=0.0055pu.
In T&D system, $X_{2sys} \approx X_{1sys}$

In the very extreme case that the *two* 26.5MVA Tx of Fanling KCR s/s were at full load and dominated by negative sequence current (i.e. I_2=2, I_1=0, I_0=0), V_2= $|-I_2X_{2sys}| \approx$ 0.011pu, much smaller than the 2% limit. 11



(a) Positive and (b) negative sequence network

Impact of voltage and current Imbalances

Consequently, voltage imbalance is no longer a problem in the CLPP network, and V_2 monitor at PCC may be not necessary.

Only current imbalance of 1-phase traction load will cause impact to 3-phase power system at substation and generator.

To assess imbalance by symmetric component approach

Recall:

$$\begin{bmatrix} \mathbf{I}_0 \\ \mathbf{I}_1 \\ \mathbf{I}_2 \end{bmatrix} = \tfrac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & h & h^2 \\ 1 & h^2 & h \end{bmatrix} \begin{bmatrix} \mathbf{I}_A \\ \mathbf{I}_B \\ \mathbf{I}_C \end{bmatrix}$$

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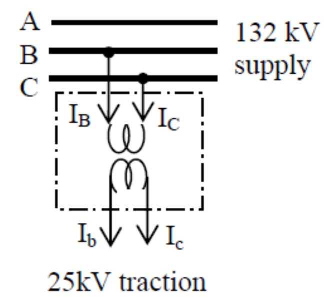
The imbalance due to $\mathbf{I}_2$ is $|\mathbf{I}_2| / |\mathbf{I}_1|$. (h is $\underline{/120°}$ operator.)

Current imbalance at traction substation

Case 1: One transformer of *B-C* connection

Assume the Tx secondary current is 1 unit. In pu system, the Tx primary and second current are equal, symbolically $[\mathbf{I}_P]=[\mathbf{I}_S]$, i.e.



$$\begin{bmatrix} \mathbf{I}_A \\ \mathbf{I}_B \\ \mathbf{I}_C \end{bmatrix} = \begin{bmatrix} \mathbf{I}_a \\ \mathbf{I}_b \\ \mathbf{I}_c \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix}$$

$$\begin{bmatrix} \mathbf{I}_A \\ \mathbf{I}_B \\ \mathbf{I}_C \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix} \Rightarrow \begin{bmatrix} \mathbf{I}_0 \\ \mathbf{I}_1 \\ \mathbf{I}_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0.577\underline{/90°} \\ 0.577\underline{/-90°} \end{bmatrix}$$

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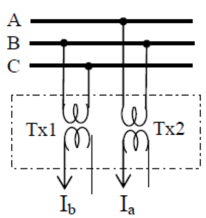
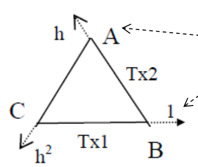
Therefore, current imbalance = $|\mathbf{I}_2| / |\mathbf{I}_1|$ = 100 %

Case 2: Two transformers of equal loading





I_a of Tx2 (*A-B*) leads I_b of Tx1 (*B-C*) by 120°.

Using h operator,
I_a=h will lead I_b=1 by 120°.

At 25 kV:

Tx1 (*B-C*)	Tx2 (*A-B*)
$\mathbf{I}_b$=1	$\mathbf{I}_a$=h
$\mathbf{I}_c$=-1	$\mathbf{I}_b$=-h

At 132kV:

$$\begin{bmatrix} \mathbf{I}_A \\ \mathbf{I}_B \\ \mathbf{I}_C \end{bmatrix} = \begin{bmatrix} h \\ 1-h \\ -1 \end{bmatrix} \Rightarrow \begin{bmatrix} \mathbf{I}_0 \\ \mathbf{I}_1 \\ \mathbf{I}_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 1.1547\underline{/90°} \\ 0.577\underline{/-150°} \end{bmatrix}$$

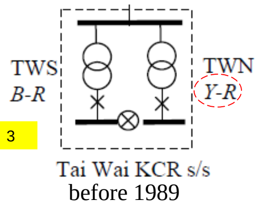
Current imbalance = $|\mathbf{I}_2| / |\mathbf{I}_1|$ = 50 %

Assumptions for simplification

The above calculation assumes Tx primary and secondary pu voltages are equal (i.e. $\mathbf{V}_P=\mathbf{V}_S$), resulting the primary and secondary pu current are also equal (i.e. $\mathbf{I}_P=\mathbf{I}_S$). In addition, all traction loads are assumed of equal power factor (i.e. all current are spaced by 120°) such that the current can be simply related to 1, h or h^2

In actual operation, the current magnitudes & power factors are different, and the current imbalance should be higher, as illustrated in case 3.

Case 3: Two transformers with unequal loading



Assume Tx loading S TWS: 5MVA
TWN: 12MVA

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For a system having both 3-ph and 1-ph, $I_{pu}=\sqrt{3}\,S/S_b$

Using a base of S_b=100MVA, the Tx current are:

$I=\sqrt{3}\ 0.05 = 0.087$pu for TWS

$I=\sqrt{3}\ 0.12 = 0.208$pu for TWN

At 25 kV:

TWS *B-R or C-A*	TWN *R-Y or A-B*
$I_c= 0.087h^2$ $I_a=-0.087h^2$	$I_a= 0.208h$ $I_b=-0.208h$

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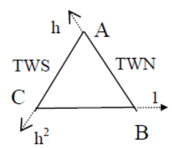
Assign phase sequence ***R-Y-B*** as ***A-B-C***



At 132kV:

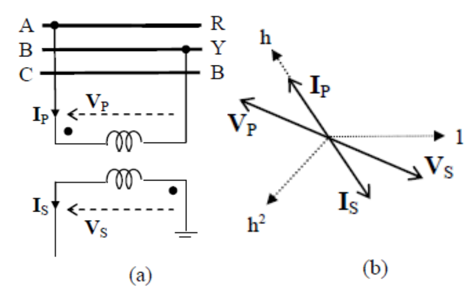
$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} \mathbf{0.208h}-0.087h^2 \\ -0.208h \\ 0.087h^2 \end{bmatrix} \Rightarrow \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 0 \\ \mathbf{0.17\angle 90^\circ} \\ 0.104\angle 125^\circ \end{bmatrix}$$

Check: : In pu
0.05+0.12=**0.17**

Current imbalance = $|I_2|/|I_1|$ = 61.4 % (>50% for equal load)

Special arrangment for phase connection

Traditional phase sequence is R-Y-B, and the standardized phase connection for 1-ph Tx should be either *R-Y*, *Y-B* or *B-R* at 132kV supply side. However, it may be different at the 25kV consumer side.



(a) Dot notation for TWN and (b) phasor diagram

In pu system, $V_S=-V_P$ and $I_S=-I_P$

With secondary V_S reversed

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the secondary current

$I_S=I_a= -0.208h$

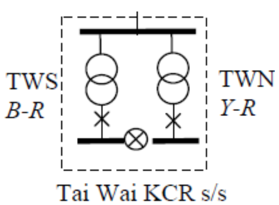
but the primay current

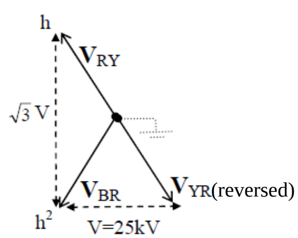
$I_P=-I_S=0.208h=I_A$ is not affected

The dot notation does not affect the primary current at 132kV at which the imbalance is to be assessed.

To avoid confusion in imbalance estimation, reversed phase connection of ***Y-R***, ***B-Y*** or ***R-B*** will be treated as non-reverse ***R-Y***, ***Y-B*** or ***B-R***.

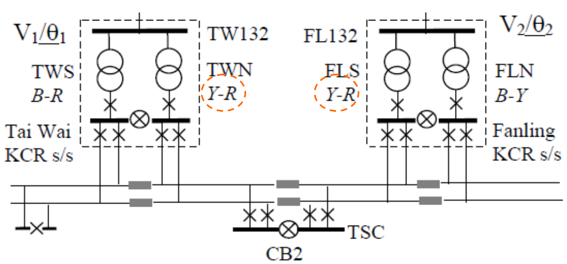
Advantage of Reverse Dot Connection





The voltage across 25kV CB (NO) is reduced by a factor of $\sqrt{3}$.

Advantage of Identical Phase Connection



With identical *Y-R*, voltage across CB2 (NO) is almost zero.

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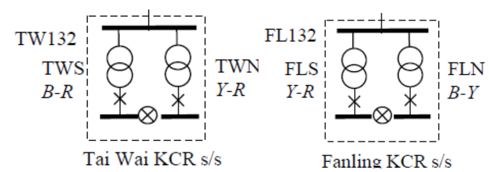
Overall Imbalance for Multi Substations

Case 4: Four transformers in two substations



At 25 kV:

TWS *B-R or C-A*	TWN *R-Y or A-B*	FLS *R-Y or A-B*	FLN *Y-B or B-C*
$I_c= h^2$ $I_a=-h^2$	$I_a= h$ $I_b=-h$	$I_a= h$ $I_b=-h$	$I_b= 1$ $I_c=-1$

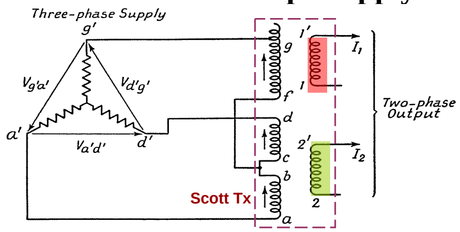
At 132kV:

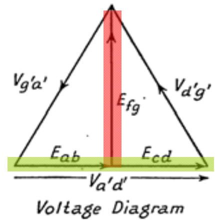
$$\begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix} = \begin{bmatrix} 2h-h^2 \\ 1-2h \\ h^2-1 \end{bmatrix} \Rightarrow \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 2.309\angle 90^\circ \\ 0.577\angle 150^\circ \end{bmatrix}$$

Overall current imbalance becomes $|I_2|/|I_1|$ = 25 %. 25

(The imbalance at each substation is still 50%.)

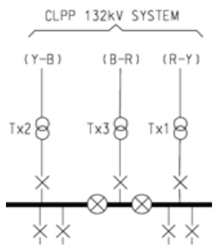
Scott Tx connection for 3-ph supply to two 1-ph outputs





If turn ratio ab:cd:fg=1:1:√3, perfect 3-ph balance may be achieved by Scott Tx.

Disadvantage: one Tx failure results in loss of supplies to two sections.
⇒ Capacity of the standby Tx caters for the loading of two sections



Advantage of separate 1-ph Tx:
One Tx failure results in temporary loss of supply of only one section.
Supply can be restored shortly by switching in the third standby Tx (e.g. Tx3 at Fanling KCR s/s).
⇒ Capacity of the standby Tx caters the loading for one section only.

Summary of Overall Imbalance for equal Tx loading

Imbalance for multi-Tx in a system						
Number of Tx	1	2	3	4	5	6
Overall Imbalance	100%	50%	0%	25%	20%	0%

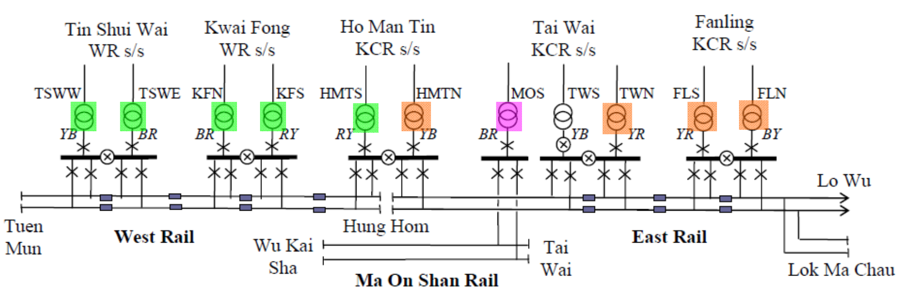
The above (ideal) is for equal loading and power factor.
In reality, the imbalance is higher.

It is expected current imbalance will be normally reduced with more Tx in the system.

KCR system in 2010, with three lines and 5 substations

Total 10 Tx in KCR system:

ER Line has 4 Tx in 3 s/s
MOSR Line has only 1 Tx 3
WR Line has 5 Tx in 3 s/s



HMTN and TWS are of same phase (*Y-B*), but there is no track section cabin 6 (TSC) between them. Therefore, one Tx (TWS) is at standby.

All Tx are of 26.5MVA rating, except TWN and TWS upgraded to 38MVA.

(Phase only depicts the 25kV Tx secondary winding connection.
Other standby Tx are not shown for simplicity) 25 35 39 40

Imbalance impact analyses of multi-line ac traction system

KCR system parameters at peak load

System	Car	Length (km)	Headway (min)	Section	Load Ratio Tx	Load Ratio System
ERL	12	40	2.5	4	1.0	4
MOL	4	12	3	1	0.33	0.33
WRL	7	34	3	5	0.33	1.65

Assumptions 32

1. Tx current will be proportional to the number of car and the length of the system, but is inversely proportional to the headway and the number of section.
2. For simplicity, each Tx in ERL is assumed to have a current of 1 unit.
3. Tx in the same system are assumed of equal loading.

Observation

1. The ratio of system loadings of ERL:MOL:WRL is 4.0:0.33:1.65=12:1:5.
2. Ma On Shan Line (MOL) has only one section (or Tx) and the imbalance is inevitably 100%. However, its loading is only 1/12 of ERL, and the impact on overall imbalance is the smallest.
3. ERL has the highest loading, and its impact on overall imbalance (critical to generator with limit of 5% only) is the highest.

Case 5: Ten transformers in five substations

Tx loading and current imbalance in KCR system in 2010 23

Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	FLS [1]	FLN [1]	
Tai Wai	TWN [1]		MOS [0.33]
Ho Man Tin	HMTS [0.33]	HMTN [1]	
Kwai Fong	KFS [0.33]		KFN [0.33]
Tin Shui Wai		TSWW [0.33]	TSWE [0.33]
Current Imbalance	ERL [2-2-0]		50%
	WRL [0.67-0.33-0.67]		20%
	Overall [2.67-2.33-1]		25.5%

In Case 4, the ERL in 90' with 4 Tx has an overall imbalance of 25%. 20

In this Case 5, the imbalance for ERL alone is 50% and the overall imbalance of KCR is 25.5%

It is surprising that with a much increase in the number of Tx from 4 (Case 4) to 10 (Case 5), the overall imbalance was abnormally increased.

The reason is due to the phase change of TWS in 2004, as explained in Case 6.

27 35 36

Case 6: Eight transformers in four substations

Imbalance in early 2003 (without Ho Man Tin s/s)

Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	FLS [1]	FLN [1]	
Tai Wai	TWN [1]		TWS [1]
Kwai Fong	KFS [0.33]		KFN [0.33]
Tin Shui Wai		TSWW [0.33]	TSWE [0.33]
Current Imbalance	ERL [2-1-1]		25%
	WRL [0.33-0.33-0.67]		25%
	Overall [2.33-1.33-1.67]		16.5%

The 4 Tx in **ERL** had 3 different phase connections

Imbalance of **ERL** was doubled in 2004

Imbalance with change in 132kV connection of TWS in 2004

Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	FLS [1]	FLN [1]	
Tai Wai	TWN [1]	**TWS** [1] ← - - - - - - •	
Kwai Fong	KFS [0.33]		KFN [0.33]
Tin Shui Wai		TSWW [0.33]	TSWE [0.33]
Current Imbalance	ERL [**2-2-0**]		**50%**
	WRL [0.33-0.33-0.67]		25%
	Overall [2.33-**2.33-0.67**]		**31.3%**

Overall Imbalance also doubled

27 35

Impact of current imbalance to generator protection

All the above analyses are for traction load alone. Although the current imbalance appears high, the current imbalance experienced by generator should be less than the 5% limit because ac traction is a small fraction of CLPP load (about 1%), and the tripping of generator appears unlikely.

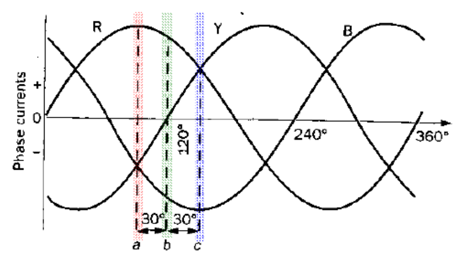
At present, the hazard of generator tripping may still exist, because
(a) the Tx loads in a line are not equal
(b) the power factor are not equal
(c) peak load periods of KCR (around 8am) and CLPP (around 11am) are different.
(d) the train load is momentary in nature, and usually has a very large value during the first few seconds at train-start. (Some CLPP generators may trip if I_2 exceeds 5% for 6 second.)

For instance, total peak load of the 4 Tx in ERL was about 43 MW (30-min average), but the recorded momentary load was higher than the Tx rating in Tai Wai s/s. Thus, the TWN and TWS were upgraded from 2×26.5MVA to 2×38MVA in 2009.

The most hazardous period with multi s/s should be at 2004 with the highest overall imbalance of 31.3%. 26

With the commissioning of MOS and the completion of Kowloon Southern Link 25 (KSL), the overall imbalance was gradually reduced to 25.5% in 2010 (Case 5).

Impact of current imbalance to machine stator (1)

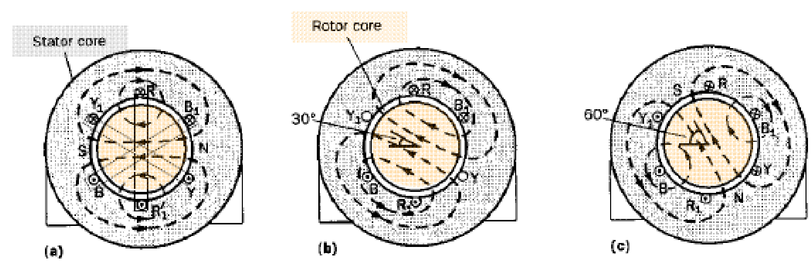


Balanced 3-phase stator current

Rotating field of 3-phase machine

The stator balanced current I_1 will establish a field rotating clockwise (i.e forward).

If current is unbalanced, I_0 will set up a field stationary, and I_2 set up a field rotating backwards.

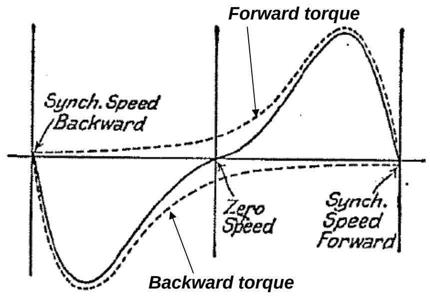


Distribution of magnetic flux due to 3-phase current (using right-hand rule)

Impact of current imbalance to machine stator (2)

If the imbalance I_2/I_1 is, say 10%, the machine forward torque is reduced by 10%, and machine efficiency/performance is degraded.

If the imbalance is 100%, the machine forward torque is zero. This occurs in single phase motor without compensated auxiliary winding.



Torque-slip curve for single-phase motor without auxiliary stator winding

An uncompensated 1-phase motor has a pulsating field.

Analytically, the pulsating field can be resolved to two components: forward and backward.

At standstill (i.e. zero speed), net machine torque is zero, and motor cannot start.

Moreover, negative sequence stator current I_2 will create extra I_2^2 R losses in the stator windings and in the T & D network.

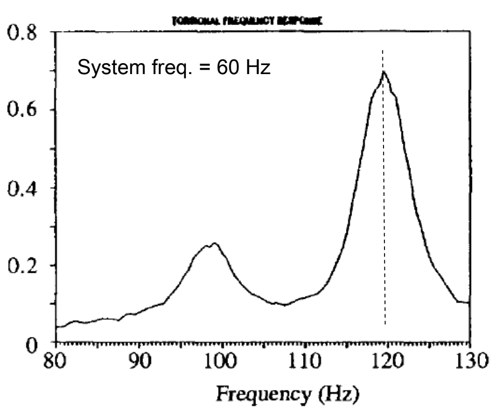
Impact of current imbalance to machine rotor

The negative sequence current is similar to the positive sequence current, except that the resulting reaction field rotates counter to the dc field system and hence produces a flux which cuts the rotor at twice the rotational velocity, thereby inducing double frequency currents in the field system and in the rotor body, creating additional hysteresis loss P_h and eddy current loss P_e. In general, both $P_h = k_h f B_m^x$ and $P_e = k_e f^2 B_m^2$ will increase with the frequency *f*.

The resulting eddy-currents (proportional to f^2) are very large and cause severe heating of the rotor. So severe is this effect that a single-phase load equal to the normal 3-phase rated current can quickly heat the brass rotor slot wedges to the softening point; they may then be extruded under centrifugal force until they stand above the rotor surface, when it is possible that they may strike the stator iron. Overheating of the wedges may be sufficient to anneal them enough to result in rupture in shear. Concentration of heating occurs on portions of the coil binding rings and here surface fusion has been known to occur.

I_2 Impact: Super-synchronous resonance to turbine blade

Other than the above well known adverse effects, turbine blade super-synchronous resonance is one of the most serious problems. The severity of negative sequence current problems resurfaced after the turbine blades of a nuclear power plant in a country of Southeast Asia were broken and almost caused a severe nuclear disaster.



It was because the double frequency component of I_2 may match the mechanical resonance of the turbine blades due to the frequency deviation and induce the supersynchronous resonance.

Impact of current imbalance to energy consumption

The negative sequence current I_2 creates a stator field (of double frequency $2f_0$) rotating in opposite direction to the rotor motion, which will downgrade generator performance/efficiency, and overheat the rotor. For a total generation of, say 6000MW, a very slight increase of, say, 0.1% generator output (e.g. to cover the additional losses) represents an undue increase of 6MW.

If a system generation is equally shared by nuclear, gas and coal, the overall generation efficiency roughly equals to (0.33+0.55+0.35)/3=0.41, and the increase of rate of fuel waste will be amounted to 6/0.42=14.6MW. This extra increase of fuel cost will be shared by all consumers at large.

Usually, the ac traction load is a small fraction of the total system generation and a small percentage decrease in generator efficiency may not be noticeable. For instance in 2009, the CLPP demand is 6389MW and the 30-minute average peak demand of KCR is about 64MW.

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Case studies here are based on simplified assumptions/data of KCR. Without the CLPP generator parameters and the realistic imbalance data, it is impossible to estimate the actual energy waste due to the traction imbalance.

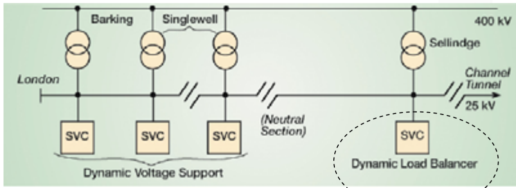
Combat imbalance by 33kV Dynamic Load Balancer (ABB)

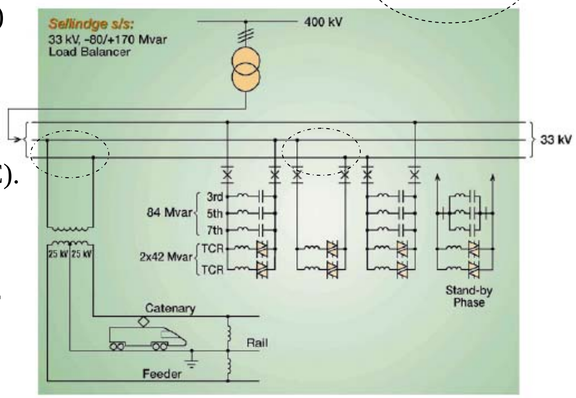
Installed at high-speed rail of Channel Tunnel Rail Link at Sellindge s/s near Dover.
Rail length 109 km between London and Paris.
Total time travel: 2hr 20min.

(HK-GZ 150-km within 2hr.)

The Balancer is regarded as an asymmetrical controlled stator var compensator (SVC).

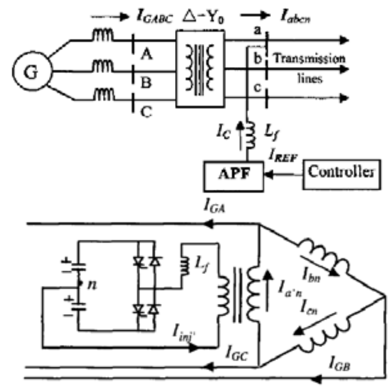
The Balancer is controlled to compensate I_2 drawn from 400kV and to regulate power factor to unity.



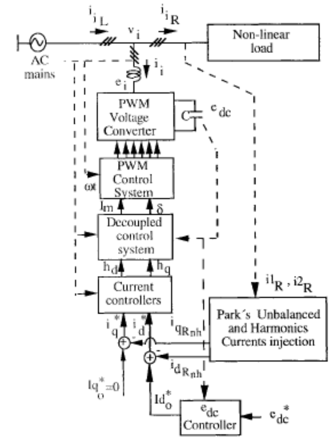


Combat imbalance by active power filter (APF)

Active power filter based on voltage source inverter



Active power filter with unbalance current control



However, all these combating methods are complicated, and installation/operation costs are very high.

Cost-effective & pragmatic measures to suppress imbalances

In 2003, the system has the lowest overall imbalance of 16.5% because the load ratio of [2.33:1.33:1.67]=[7:4:5] is most evenly distributed (Case 6). 26
In 2004, with a weak load ratio of [2.33:2.33:0.67[=[7:7:2], the imbalance of 31.3% is the highest since 90's.

At present, the load ratio of [2.67:2.33:1]=[8:7:3] is still weak (Case 5), but it 25 may be pushed to [6:6:6] by appropriate modification of the existing of 132kV supply, such that the imbalance may reach zero.

Constraint consideration in the modification: 23

(a) In Tai Wai KCR s/s, TWN, TWS (standby) and MOS have to be of three different phase connections. 39

(b) Each Tx pair (TSWE/KFN, KFS/HMTS or TWN/FLS) is of same phase, such that the voltage stress across the circuit breaker at TSC is zero.

(c) HMTN has the same phase as the standby TWS (since no TSC).

Scheme I in three stages

Stage Ia: Swapping HMTN and MOS			
Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	FLS [1]	FLN [1]	
Tai Wai	TWN [1]	**MOS** [0.33] ←	•
Ho Man Tin	HMTS [0.33]	• →	**HMTN** [1]
Kwai Fong	KFS [0.33]		KFN [0.33]
Tin Shui Wai		TSWW [0.33]	TSWE [0.33]
Current Imbalance	East Rail [2-**1**-**1**]		**25%**
	West Rail [0.67-0.33-0.67]		20%
	Overall [2.67-**1.67**-**1.67**]		**16.6%**

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ERL then has 3 different phase connections (instead of 2)
Loading ratio of the 3 rail systems is improved to [2.67:1.67:1.67]=[8:5:5]
(In case 5, loading ratio is [2.67:2.33:1]=[8:7:3] and overall imbalance is 25.5%)

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Stage Ib: Change Tx pair of HMTS/KFS from ***R-Y*** to ***Y-B***			
Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	FLS [1]	FLN [1]	
Tai Wai	TWN [1]	MOS [0.33]	
Ho Man Tin	→	**HMTS** [0.33]	HMTN [1]
Kwai Fong	→	**KFS** [0.33]	KFN [0.33]
Tin Shui Wai		TSWW [0.33]	TSWE [0.33]
Current Imbalance	East Rail [2-1-1]		25%
	West Rail [**0-1**-0.67]		**52.9%**
	Overall [**2-2.33**-1.67]		**9.6%**

With a better loading ratio of [2:2.33:1.67]=[6:7:5], the overall current imbalance is further suppressed to 9.6%, but the imbalance of WRL is raised to 52.9%, because WRL Tx have only 2 phases: *Y-B* and *B-R* 38

Stage Ic: Change TSWW from ***Y-B*** to ***R-Y***			
Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	FLS [1]	FLN [1]	
Tai Wai	TWN [1]	MOS [0.33]	
Ho Man Tin		HMTS [0.33]	HMTN [1]
Kwai Fong		KFS [0.33]	KFN [0.33]
Tin Shui Wai	**TSWW** [0.33]	←	TSWE [0.33]
Current Imbalance	East Rail [2-1-1]		25%
	West Rail [**1-0.67**-0.67]		**20.0%**
	Overall [**2.33-2**-1.67]		9.6%

With Tx of 3 different phase connections in WRL, the imbalance resumes 20%

Overall imbalance of [2.33:2:1.67]=[7:6:5] remains at 9.6% 37

Scheme II in two stages

Stage IIa: Change HMTN from ***Y-B*** to ***B-R***

Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	FLS [1]	FLN [1]	
Tai Wai	TWN [1]		MOS [0.33]
Ho Man Tin	HMTS [0.33]	→	**HMTN [1]**
Kwai Fong	KFS [0.33]		KFN [0.33]
Tin Shui Wai		TSWW [0.33]	TSWE [0.33]
Current Imbalance	ERL [2-1-1]		25%
	WRL [0.67-0.33-0.67]		20%
	Overall [2.67-1.33-2]		19.2%

23 As TWS has to be of same phase with HMTN, Tai Wai KCR s/s will have 2 Tx (TWS and MOS) of same phase, violating constraint (a). 35

However, as TWS is of standby, this ‘violation’ should be acceptable.

With a loading ratio of [2.67:1.33:2]=[8:4:6], the overall current imbalance is reduced to 19.2%.

Stage IIb: Change Tx pair HMTS/KFS from ***R-Y*** to ***Y-B***			
Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	FLS [1]	FLN [1]	
Tai Wai	TWN [1]		MOS [0.33]
Ho Man Tin	→	**HMTS** [0.33]	HMTN [1]
Kwai Fong	→	**KFS** [0.33]	KFN [0.33]
Tin Shui Wai		TSWW [0.33]	TSWE [0.33]
Current Imbalance	East Rail [2-1-1]		25%
	West Rail [0-1-0.67]		**52.9 %**
	Overall [2-2-2]		**0%**

With a loading ratio of [2:2:2]=[6:6:6], the overall current imbalance is reduced to almost zero.

All the above measures only require to change the 132kV phase connections of existing Tx in various s/s and are very cost-effective. Moreover, the train services should not be disturbed because there are total 5 standby Tx in KCR.

3

Conclusion (1)

AC traction is of single phase, and imbalance to 3-phase supply is inevitable. According to the supply rule of CLPP, the limit is 2% for voltage imbalance at substation and 5% for current imbalance at generator.

CLPP has regularly monitored the negative sequence voltage V_2 of 132kV traction supply at point of common coupling (PCC). V_2 is well within the 2% voltage limit because CLPP 132kV system is very stiff, and voltage imbalance is no longer a problem in CLPP system. Impact of only current imbalance is of concern for power system operation.

ERL may be the only single-phase traction system (having three or more transformers) in the world that has over 50% current imbalance by itself. ERL appears ridiculous in design since it is the largest ac traction system in CLPP.

KCR is the second largest consumer load in CLPP, but its average load is only about 1% of the CLPP system total. Although generator tripping due to ac traction load is unlikely, there is a possible hazard of super-synchronous resonance, leading to turbine blade damage.

Conclusion (2)

Moreover, the negative sequence current will create a rotating field opposite to generator rotor motion, inducing a double frequency current in the rotor and the much increased iron losses will heat the rotor, jeopardizing the generator performance/efficiency, resulting an undue increase of fuel consumption.
The extra cost of fuel consumption will be shared by all customers.

To eliminate the design ‘abnormality’, to enhance generator efficiency and performance, and to avoid the unnecessary waste of energy, two pragmatic remedial measures have been proposed to appropriately rearrange the 132kV phases connecting the traction transformers in local traction substations.
It is expected the overall current imbalance will be much reduced (to even zero).

If an energy saving measure is beneficial to both consumers and utility, as well as cost-effective, it is expected a reputable utility will take immediate action for rectification.

About the speaker

Dr. C.T. Tse was the Asso Prof in the EE Depart of PolyU. Before joining the Hong Kong Polytechnic in 1990, Mr. Tse was the Planning Engineer of System Planning Branch in CLP. His main duty was to look after power system stability and the ‘abnormal’ loads, such as arc furnace and traction. During his 20-year service in PolyU, Dr. Tse has engaged in 6 consultancy investigations associated traction power supply (3 with KCR, 2 with MTR and one with KCR/MTR). One of his research works was supported by MTRCL via the PolyU Teaching Company Scheme. As the Visiting Associate Professor with the EE Dept after retirement since September 2010, three of his taught MSc subjects are associated with traction systems.

Acknowledgement

The speaker would like to express his gratitude to the 2 co-authors in the preparation of paper *Impact of Imbalance of Single-Phase Traction Load to Three-Phase Power System*, submitted to HKIE Transaction, and the materials for this seminar.

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Appendix: Per Unit in Mixed Systems of 1-ph and 3-ph

In 1-ph system
$\mathbf{S} = \mathbf{V}\,\mathbf{I}^*$, $S_b = V_b I_b$ and $\mathbf{S}_{pu} = \mathbf{V}_{pu}\,\mathbf{I}^*_{pu}$
(Subscript b stands for base.)
In 3-ph system
$\mathbf{S} = \sqrt{3}\,\mathbf{V}\,\mathbf{I}^*$, $S_b = \sqrt{3}\,V_b I_b$ and $\mathbf{S}_{pu} = \mathbf{V}_{pu}\,\mathbf{I}^*_{pu}$
Their pu notation $\mathbf{S}_{pu} = \mathbf{V}_{pu}\,\mathbf{I}^*_{pu}$ are the same.

For a mixed system, the 1-ph Tx may be regarded as 3-ph delta/delta Tx (but with zero load on one 25kV circuit.)

At LV (i.e. 25kV):
$I = S/V$
$I_b = S_b / \sqrt{3}\,V_b$

$$I_{pu} = \frac{S/V}{S_b/\sqrt{3}V_b} = \frac{S\sqrt{3}}{S_b V_{pu}} = \sqrt{3}\ S_{pu}/V_{pu}$$

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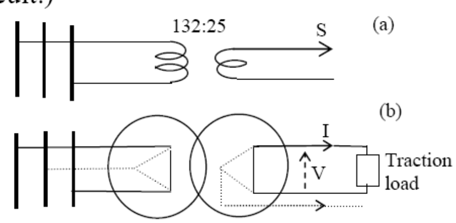

(a) 1-ph Tx represented by (b) fictitious 3-ph Tx

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ABBREVIATIONS

f_0: System frequency of 50Hz or 60Hz
$2f_0$: Double frequency of 100Hz or 120Hz
R-Y-B: phase sequence of 3-phase system
A-B-C: alternate phase sequence representation
h: $\angle 120°$ operator
V_0, V_1, V_2: zero, positive and negative sequence voltage
I_0, I_1, I_2: zero, positive and negative sequence current
pu : per unit
S_b, V_b, I_b: base values of MVA, voltage and current
s/s: substation or substations
PCC: 132kV s/s at point of common coupling
X_{1SYS}, X_{2SYS}: Source positive/negative sequence Thevenin reactance at PCC
NO: normally opened
CLPP: CLP Power
MTRCL: MTR Corporation Limited
MTR: 1.5kV dc railway system
KCR: 25kV ac railway system
ERL: East Rail Line
WRL: West Rail Line
MOL: Ma On Shan Line

KSL: Kowloon Southern Link
ETS: East Tsim Sha Tsui Extension or East Tsim Sha Tsui Station
TSC: track section cabin
Tx: transformer or transformers
V_P, V_S: Tx primary and secondary voltages
I_P, I_S: Tx primary and secondary current
FLN: Fanling North Tx (Tx1)
FLS: Fanling South Tx (Tx2)
TWN: Tai Wai North Tx (Tx1)
TWS: Tai Wai South Tx (Tx2)
MOS: Tx for MOL at Tai Wai KCR s/s (Tx3)
HMTN: Ho Man Tin North Tx (Tx2)
HMTS: Ho Man Tin South Tx (Tx1)
KFS: Kwai Fong South Tx (Tx1)
KFN: Kwai Fong North Tx (Tx3)
TSWE: Tin Shui Wai East Tx (Tx1)
TSWW: Tin Shui Wai West Tx (Tx3)

END

IEEE/IMC
Seminar

More Proper and Economic Design of Shatin-Central-Link

Delivered by Dr C T Tse
Jun-11, 2012 (Mon)
FJ304, PolyU

Contents

Abbreviations

MTRC: MTR Corporation
KCR: 25kV single phase ac railway system under MTRC
ERL: East Rail Line
WRL: West Rail Line
MOL: Ma On Shan Line
SCL: Shatin Central Link
NSL: North South Line
EWL: East West Line
Tx: Transformer or transformers
CB: Circuit breaker or circuit breakers
CLPP: CLP Power
HEC: Hong Kong Electric
SCADA: Supervisory control and data acquisition

s/s: Substation (132kV or 25kV)
FS: feeding station (or stations) of 132kV or 25kV, supplying power to KCR
CWB: Causeway Bay
HUH: Hung Hom
HMT: Ho Man Tin
TWA or TAWA: Tai Wai A FS
TWB or TAWB: Tai Wai B FS
ADM: Admiralty
SOV: South Ventilation Building
SHE: Shatin
CWS: Chik Wan Street
TPK: Tai Po Kau
FNL: Fanling
PCC: Point of common coupling

m jump to slide-m

n return to slide-n

Mass Transit Systems in HK

The 3 major mass transit systems of MTRC have different supply sources.

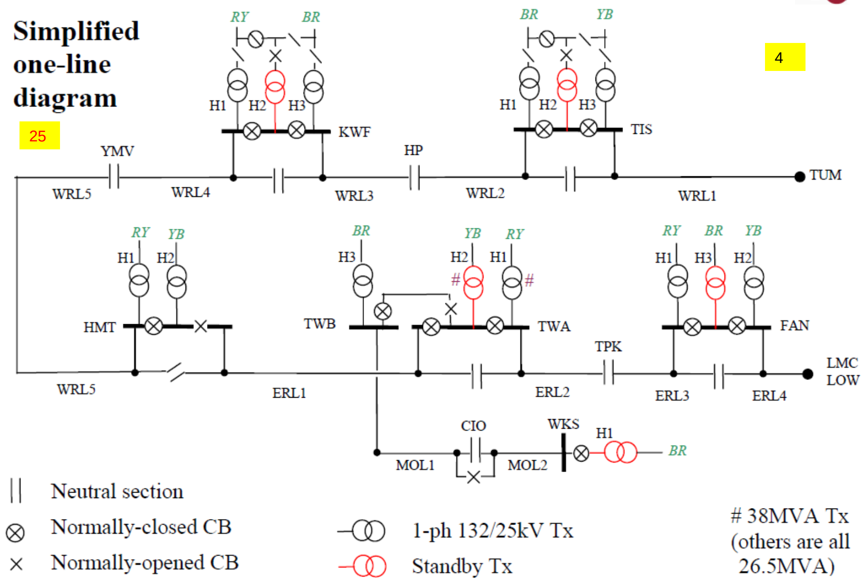
- LRT: 750V DC
- MTR: 1.5kV DC
- KCR: 25kV 1-phase AC

At present, KCR is energized by CLPP and consists of East Rail Line (ERL), West Rail Line (WRL) and Ma On Shan Line (MOL).
ERL has 4 sections, WRL 5 sections and MOL 1 section. The load ratio of ERL:WRL:MRL at peak is roughly 12:1:5 at 2009 [1,2].

The KCR system is fed by 13 CLPP 132kV cables via 15 132/25kV 1-ph Tx (10 on-load and 5 standby). KCR has 6 FS supplying power to 10 rail sections. Normally, each FS has two on-load Tx to reduce the voltage/current imbalance. 5

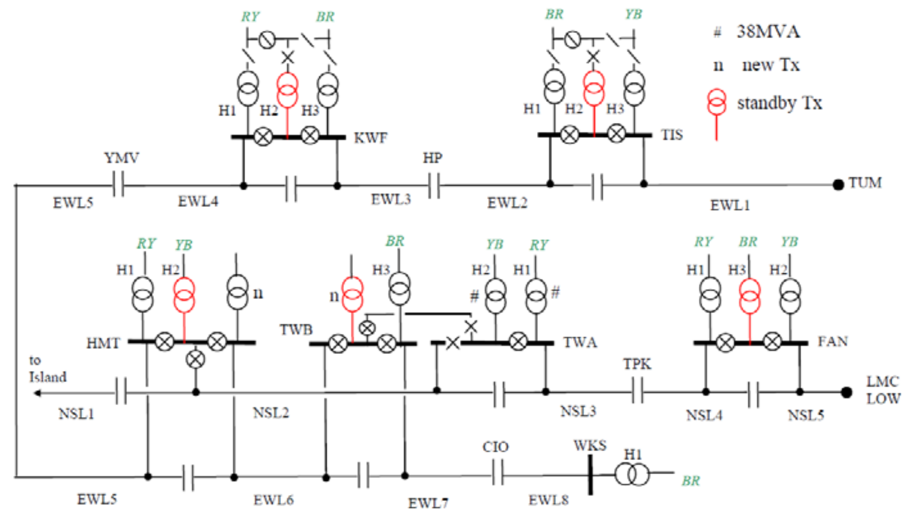
Other than imbalance, the ac traction has other power quality problems, such as voltage flicker, and voltage/current harmonics. But these problems can be easily combated by installing passive filter in each line section [3,4]

KCR system since 2009



2011 Design for future KCR with SCL

ERL will be extended to Island, to form the North South Line (NSL).
WRL and MOL will be combined/extended to form the East West Line (EWL).
NSL has 5 sections and EWL 8 sections, with 2 new Tx in CLP and 2 in HEC.



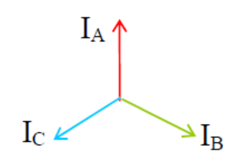
Pros and Cons of AC System vs DC System

Pros [1,2]: Fewer feeding station because per unit voltage drop ΔV is relatively small. Suitable for intercity and sub-urban (long distance) train services since (ΔV_{KCR}:ΔV_{MTR})=0.0036:1.
(The 40kM ERL has only 2 FS.) 25

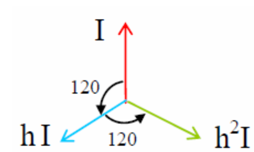
Cons [1,2] : Weaker supply security
Because of phase difference, each line-section in KCR is supplied by only one Tx (1-ph 132/25 kV). Loss of Tx will result in loss of supply of the line.
In MTR, the 1.5kV traction supply is fed by multi rectifier Tx. Loss of one or a few Tx does not affect the train supply.

Standby Tx is vital in KCR to ensure continuity of train service after Tx loss.
In early 90's there is no standby Tx in KCR. Under Tx loss, a Tx had to supply two sections and the train services had to be degraded, to avoid overload Tx. 25

Balanced 3-phase load



The 3- phase current is $I_P=[I_A, I_B, I_C]$. For balanced loading, they are of equal magnitude and spaced by 120°



Using operator h=/120°, and let I_A=I/0 be the reference, then the 3- phase current are $[I_A, I_B, I_C]$=[I, I/240°, I/120°]=[I, h^2I, h I]

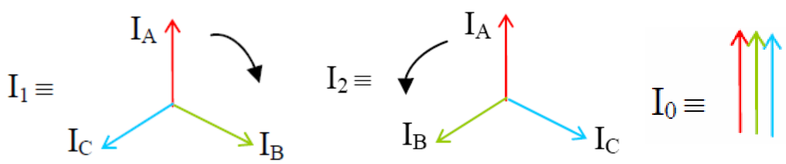
Mathematically, the *phase* current $[I_P]=[I_A, I_B, I_C]$ can be transformed to *sequence* current $[I_S]=[I_0, I_1, I_2]$, using T-matrix

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \frac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & h & h^2 \\ 1 & h^2 & h \end{bmatrix} \begin{bmatrix} I_A \\ I_B \\ I_C \end{bmatrix}$$

In short: $[I_S]=[T]\,[I_P]$, where $[I_0, I_1, I_2]$ are respectively zero-, positive- and negative-sequence current.

Physical interpretation of I_1, I_2 and I_0

3-phase power supply provides only positive sequence voltages $[V_A,V_B,V_C]$. If the 3-phases have equal load, it is balanced.
The balanced 3-ph current $[I_A,I_B,I_C]$ can be represented by a single component I_1 (clockwise), the positive sequence current.

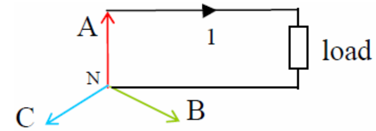


For unbalanced load, the 3-ph current will have two more sequence components: I_2 and I_0.

I_2 (anti-clockwise) is the negative sequence current, and
I_0 (stationary) is the zero sequence current.

1-phase Domestic Load (A-N)

In domestic sector, there are 4 wires: A-B-C-N, where N is the neutral.
If the current magnitude of the 1-ph load is 1-unit connected to A-N,



$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \tfrac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & h & h^2 \\ 1 & h^2 & h \end{bmatrix} \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} \Rightarrow \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \tfrac{1}{3} \begin{bmatrix} 1 \\ 1 \\ 1 \end{bmatrix}$$

$I_0=I_1=I_2=⅓$. Because I_2 and I_0 exist, the system is unbalanced.
However, this imbalance only affects the system, not the consumer.

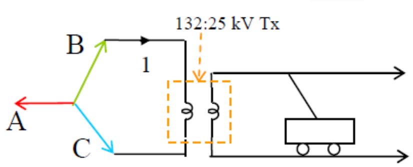
For a 3-storey building, with 3 consumers connected to 3 different phases

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \tfrac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & h & h^2 \\ 1 & h^2 & h \end{bmatrix} \begin{bmatrix} 1 \\ 1\angle 240° \\ 1\angle 120° \end{bmatrix} \Rightarrow \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}$$

because the unbalanced 'elements' I_0 and I_2 are zero, the total load is balanced. I_1 is the only balanced 'element'.

Single 1-ph Traction load (B-C)

High voltage 132kV has no neutral wire.
The ac traction has three types of load current $[I_{AB},I_{BC},I_{CB}]$.
Assuming the traction supply current at 132kV is 1-unit connected to *B-C* phase,
The imbalance is then [1].



$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \tfrac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & h & h^2 \\ 1 & h^2 & h \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix} \Rightarrow \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0.577\angle 90° \\ 0.577\angle -90° \end{bmatrix}$$

The imbalance defined by $|I_2|/|I_1|$=0.577/0.577=100%.

(Without neutral wire, I_0 is always zero.)

Double 1-ph Traction loads (B-C and A-B)

If a feeding station (FS) supplies two sections with two different phases, say *B-C* and *A-B*, then [1,2]

$$\begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \tfrac{1}{3} \begin{bmatrix} 1 & 1 & 1 \\ 1 & h^2 & 1 \\ 1 & h & 1 \end{bmatrix} \begin{bmatrix} 0 \\ 1 \\ -1 \end{bmatrix} \Rightarrow \begin{bmatrix} I_0 \\ I_1 \\ I_2 \end{bmatrix} = \begin{bmatrix} 1 \\ 0.577\angle 90° \\ 0.577\angle -90° \end{bmatrix}$$

The imbalance is reduced to 0.577/1.155=50%. Thus in KCR, a FS must have at least two on-load transformer (Tx), e.g. Tai Wai FS has 2 sections: north to Tai Po Kau and south to Hung Hom.

The above imbalance calculation is for **pure** ac traction load.
The resulting unbalanced voltage V_2 will affect other consumers connected to point of common coupling (PCC) at 132kV.
With other consumer loads (almost balanced), V_2 in should be much reduced, less than 0.11pu [1], within the CLP limit of V_{2MAX}=2%.

However, overall imbalance is critical to generator, and CLPP has set a limit of 5%.

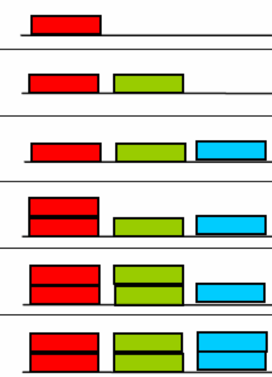
Supply Rule from CLPP Website

Type of Distortion	Type of Abnormal Load	Operational Limit
Voltage Fluctuation	Electric arc furnace	• for 132kV and below 2 %
	Motor starting	• Infrequent (intervals exceeding 2 hours) 3 % • Frequent (intervals not exceeding 2 hours) 1 %
	Rolling mill and traction (motor starting intervals not exceeding several minutes)	• Step-type change : up to 66kV 1 % 132kV ¾ % • Ramp-type change : up to 66kV 1 % /sec 132kV ¾ % /sec • Limit of total change : up to 66kV 3 % 132kV 2¼ %
Voltage Unbalance	Single phase electric traction load	• Voltage : negative sequence 2 % of positive sequence • Current into generators : negative sequences 5 % of positive sequence

This seminar will focus on imbalance impact to generator.

Overall Imbalance vs Number of Rail Section

Number of sections	Phase connections *AB* *BC* *CB*	Imbalance $\lvert I_2 \rvert / \lvert I_1 \rvert$
1		100%
2		50%
3		0%
4		25%
5		20%
6		0%



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Summary of Imbalance vs Number of Section

(a) Section	1	2	3	4	5	6	7	8	9	10
(b)Imbalance	100%	50%	0	25%	20%	0	14%	13%	0	10%
(a)×(b)	1	1	0	1	1	0	1	1	0	1

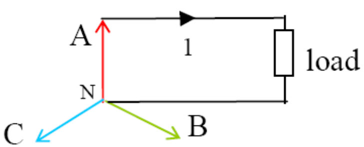
The imbalance for 3 or 3-multiple is zero.
The imbalance for non-3-multiple decreases with more sections.

In 80's, ERL has only 4 sections and the overall imbalance is 25%.

The above estimations assume each section has identical train load. 25

Imbalance due to traction load is inevitable. Although imbalance does not affect the train operation, a competent engineer in the power utility should reduce the imbalance, as far as possible, based of parameters provided by the mass transit company **at the planning stage**. These parameters include number of car per train, number of section in a line, total line length, headway (i.e. train frequency).

Imbalance in Domestic Building (1)

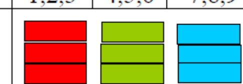


With neutral wire N, the three types of load are: I_{AN}, I_{BN}, I_{CN}

To minimize the imbalance, an engineer should evenly shares load to each phase at design stage.

For a 9-floor building, a design of phase/floor allocation can be:

	Phase connection		
	AN	BN	CN
floors	1,2,3	4,5,6	7,8,9



If the electricity consumption of each floor is identical, perfect balance can be achieved (i.e. 0% imbalance).

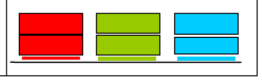
Imbalance in Domestic Building (2)

However, if floors 1,2,3 are car-park with lighting load only, imbalance occurs.

	Phase connection		
	AN	BN	CN
floors	**1,2,3**	4,5,6	7,8,9

A competent engineer should assign the phase connections as, say:

	Phase connection		
	AN	BN	CN
floors	**1**,4,5	**2**,6,7	**3**,8,9



If the upper floor loadings are equal, the imbalance is almost zero.
In reality, the engineer does not have loading information of the floors at design stage. But he should realize the car park must of much lower electricity consumption.

If one groups all car park load to one phase, and insists he has evenly allocated 3-3-3 to the 9 floors, he is unprofessional.

Traction Load Estimation at Design Stage (1)

In ac traction design, the traction load of each line section depends on the line length, number of sections, the train headway (peak or off-peak), the number of cars in each train; all information are ready at design stage. (The number of passengers per car can only be obtained by forecast.)

KCR system parameters at peak load

System	Car	Length (km)	Headway (min)	Section	Load Ratio	
					Tx	System
ERL	12	40	2.5	4	1.0	4
MOL	4	12	3	1	0.33	0.33
WRL	7	34	3	5	0.33	1.65

Assumptions [1,2]

1. Tx current will be proportional to the number of car and the length of the system, but is inversely proportional to the headway and the number of section.
2. Tx in the same system are assumed of equal loading.
3. For simplicity, each Tx in ERL is assumed to have a current of 1 unit.

Traction Load Estimation at Design Stage (2)

KCR system parameters at peak load

System	Car	Length (km)	Headway (min)	Section	Load Ratio	
					Tx	System
ERL	12	40	2.5	4	1.0	4
MOL	4	12	3	1	0.33	0.33
WRL	7	34	3	5	0.33	1.65

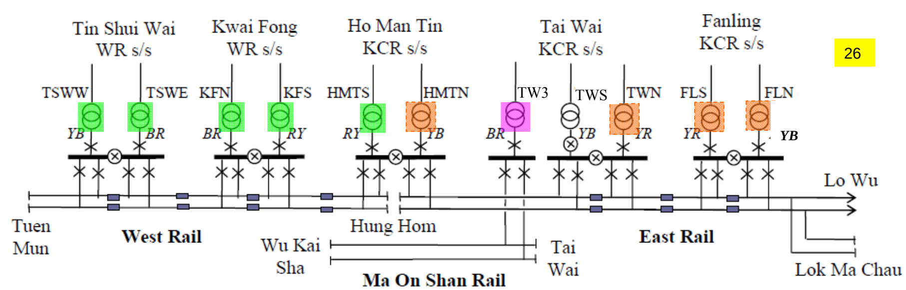
Observation

1. The ratio of system loadings of ERL:MOL:WRL is 4.0:0.33:1.65=12:1:5.
2. Ma On Shan Line (MOL) has only one section (or Tx) and the imbalance is inevitably 100%. However, its loading is only 1/12 of ERL, and the impact on overall imbalance is the smallest.
3. ERL has the highest loading, and its impact on overall imbalance (critical to generator with limit of 5% only) is the highest.

KCR system in 2010, with three lines and 5 substations

Total 10 Tx in KCR system [1,2]:

ER Line has 4 Tx in 3 s/s
MO Line has only 1 Tx
WR Line has 5 Tx in 3 s/s



HMTN and TW**S** are of same phase (*Y-B*), but there is no track section cabin (TSC) between them. Therefore, one Tx (TWS) is at standby.

All Tx are of 26.5MVA rating, except TWN and TWS upgraded to 38MVA in 2009.

(Phase only depicts the 25kV Tx secondary winding connection. Other standby Tx are not shown for simplicity)

Imbalance for Ten Sections in KCR 2010 [1]

Tx loading and current imbalance in KCR system in 2010

Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	FLS [1]	FLN [1]	
Tai Wai	TWN [1]		TW**3** [0.33]
Ho Man Tin	HMTS [0.33]	HMTN [1]	
Kwai Fong	KFS [0.33]		KFN [0.33]
Tin Shui Wai		TSWW [0.33]	TSWE [0.33]
Current Imbalance	ERL [2-2-0]		50%
	WRL [0.67-0.33-0.67]		20%
	Overall [2.67-2.33-1]		25.5%

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(Conventional color code for phases A-B-C is red-yellow-blue (*R-Y-B*).

The phase allocation to RY, YB and BR is 4-3-3 and appearing perfect. It is surprised to see that the imbalance of 25.5% for 10 sections was even worse than the 25% in late 80's when there were only 4 sections. 25

The main reason was due to the swap of phase connection of ERL in 2004.

Phase Swap at Tai Wai FS in 2004

ERL is the dominant line in KCR with 3 times Tx loading to those in other lines. Before 2004, ERL had 3 types of phase connections. Since 2004, it had only 2 types..

ERL before 2004 ERL since 2004

However the Utility C-Engineer claimed he only concerned the imbalance of entire KCR (rather than a single line) and he had most evenly allocated 4-3-3 to the ten Tx.

4-3-3 phase connection Actual loading of 10Tx

It appears he had ignored the relative loading of the section, which can be easily derived from the design parameters at planning stage that the ERL Tx should have much higher load. 21

Suggestions for More Proper Design of KCR

Stage IIa: Change HMTN from ***Y-B*** to ***B-R***

Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	FLS [1]	FLN [1]	
Tai Wai	TWN [1]		TW3 [0.33]
Ho Man Tin	HMTS [0.33]	→	**HMTN [1]**
Kwai Fong	KFS [0.33]		KFN [0.33]
Tin Shui Wai		TSWW [0.33]	TSWE [0.33]
Current Imbalance	ERL [2-1-1]		25%
	WRL [0.67-0.33-0.67]		20%
	Overall [2.67-1.33-2]		19.2%

Suggestion had been made in [1] to properly re-phase the sections in two stages to evenly distribute the train load.

Theoretically, zero imbalance may be achieved.

Stage IIb: Change Tx pair HMTS/KFS from ***R-Y*** to ***Y-B***

Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	FLS [1]	FLN [1]	
Tai Wai	TWN [1]		TW3 [0.33]
Ho Man Tin	→	**HMTS** [0.33]	HMTN [1]
Kwai Fong	→	**KFS** [0.33]	KFN [0.33]
Tin Shui Wai		TSWW [0.33]	TSWE [0.33]
Current Imbalance	East Rail [2-1-1]		25%
	West Rail [0-1-0.67]		**52.9 %**
	Overall [2-2-2]		**0%**

However, as traction load fluctuates, the imbalances (although not zero) must be much reduced by this re-phasing.

Imbalance affected by Passenger Density

The previous imbalance estimations are based on train load being proportional to the number of car in one section, resulting that the load in each ERL section was 3 times of that in WRL or MOL.

This information should be well known to the Utility design engineer. In reality, the load is much affected by the passengers in each car. It is well recognized that the ERL has more passengers. With a conservative assumption that ERL passenger being double, the relative loading becomes 6 times. It can be shown the imbalance will increase from 25.5% to 35.5%.

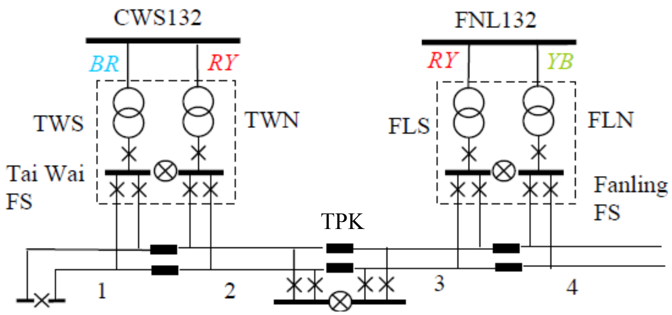
Similar to the domestic consumers, which type of phase connected does not affect the train operation. The phase connection only affects the overall imbalance of the 3-ph power system. It is the responsibility of utility engineer to look after the imbalance issue.

All the above imbalance estimations are based on some simplified assumptions. The actual imbalance can be easily obtained from SCADA of all 400/132 kV Tx loading, or from the 132/25 kV Tx loading.

The phase swap in 2004 not only increased the overall imbalance leading to giant waste of fuel energy, but also decreased the reliability of the traction supply.

Supply Reliability of KCR Feeder Station

ERL from late 80's to 2004



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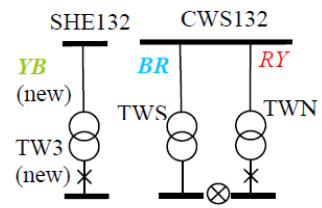
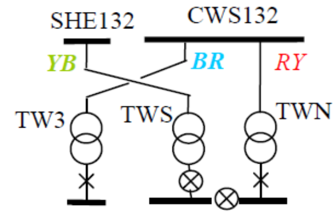
21
26

Before 2004, ERL has 4 sections supplied by 4 infeed cables of 3 different phase connections. However, loss of any 132kV infeed s/s will result in loss of all Tx in one KCR s/s.

Phase Swap at Tai Wai FS in 2004



To improve the supply reliability at Tai Wai, it was decided to increase the number of 132kV infeed s/s from one to two, by introducing a third cable (*YB*) from SHE132 to directly feed Tai Wai FS



However, the new *YB* infeed from SHE132 was connected to the old TWS (which became standby). The old *BR* infeed was reconnected to the new TW3, supplying power to a new rail system MOL.

Since then, ERL became the only rail system in the world with 4 traction Tx but having only two phase connections (*RY* and *YB*) and with abnormally high current imbalance.

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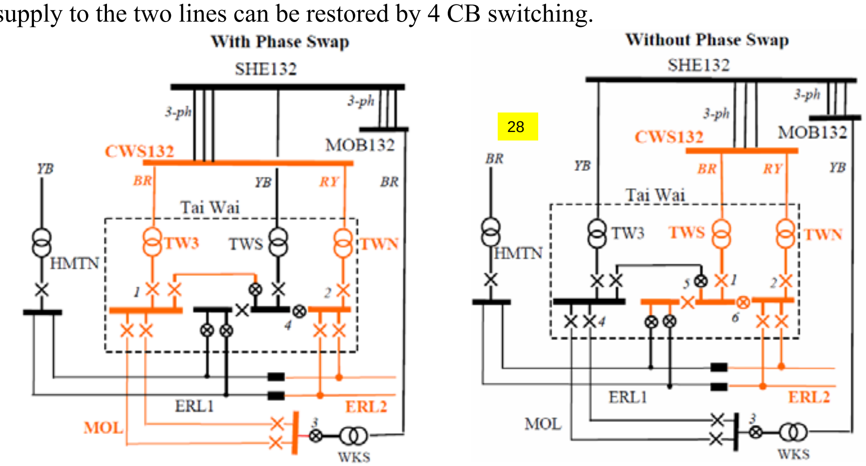
Traction Supply Reliability with Phase Swap

Because the new cable from SHE132 was put standby, loss of CWS132 will lose two lines and the supply reliability had no improvement. Nevertheless, power supply to the two lines can be restored by 4 CB switching.



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The C-Engineer said the aim of phase swap was to avoid putting two eggs in one basket (i.e. both supply and standby to ERL2 are from CWS132) and that power restoration procedure was simple (total 4 switching).

Advantage if without Phase Swap

If there is no phase swap, only one line is lost and the power supply can be restored by 6 CB switching. It appeared that the C-Engineer had ignored a third line (egg) and another standby Tx at WKS. The switching sequence should be documented/labeled in the control room, and remote CB switching for restoration is a simple task to the well trained MTRC operators.

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A major advantage of 'without Swap' is that the 3 phase connections could continue in ERL (dominated line in KCR), with minimum allowable imbalance of 25%.

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Another advantage was the project of introducing new supply was simplified and more economic, and train service was not affected without swapping.

Because changing phase connections again would affect train services, the C-Engineer opined that there was no point of re-phasing according to my recommendations in the 2010 seminar.

In 2004, without standby Tx at Tai Wai FS, swap was allowed. Now with total 5 standby Tx, why the re-phasing will affect train services?

Incentives to this SCL Seminar

As for the generator loss, the C-Engineer opined that generator efficiency was low, e.g. 35% for coal-fired plant, implying the loss was already 65%. Additional 0.25% loss increase due to traction imbalance was insignificant.

Finally, the C-Engineer insisted his phase assignment was correct since he had evenly allocated 4-3-3 to the 10 KCR sections. He promised to reduce the overall imbalance with the coming SCL and Express Rail.

In 2011, however, the speaker then found that the imbalance became worse with SCL. In early May 2012, the H-Company suggested PolyU to conduct study of SCL, because the responsible H-engineers were worried about the impact of one section of SCL at Island, connected to the other SCL sections via the cross-harbor tunnel. Such scenario is similar to the Channel link at the England-France [5]. 40

The aim of present seminar is to point out the weakness of the SCL design **at the planning stage**, to provide solutions, and to inform H-company that the permanent one section will result giant loss in fuel energy (long term).

(The seminar message was first announced on May-9, 2012.)

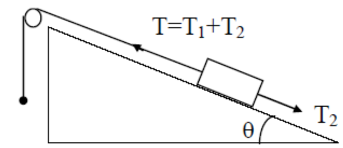
Machine Torque Affected by Imbalance

In generator, the rotor is driven by turbine (steam or gas) such that the mechanical input power P_M can be converted to electrical output power, where P_M=(turbine-torque τ)×(machine-speed N).

1-phase traction will lead to current imbalance, the unbalanced current I_2 will create a negative torque opposing the turbine drive.

Analogy of negative torque in linear motion

Consider a mass M pulled up along a smooth slope. The total tension is $T=T_1+T_2$, where $T_1=Mg.\sin\theta$ and T_2 is a force opposing the motion. The energy to pull the mass is increased due to T_2.



In the rotary motion of generator, the forward torque τ_1 will produce electrical power output. If the load is unbalanced with a negative (or backward) torque τ_2, the input torque has to be increased to $\tau=\tau_1+\tau_2$, and the input energy (fuel) will be increased.

Increase Fuel Cost due to Improper Design

Example 1: In H-system, there will be only one 1-ph Tx supplying a traction load 3MW. If the system total demand is 3000MW, calculate the loss (in MW and %) due to the ac traction.

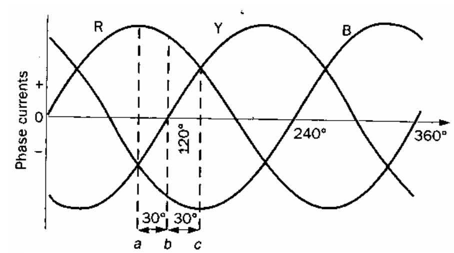
Solution: For only one 1-ph Tx, the imbalance is 100% and $\tau_1=\tau_2$. If the traction load is 3MW, the loss is also 3MW, or 0.1% of total 3000MW. In other words, a 3MW load at train becomes a 6MW load at generator. For each \$100m electricity sale to traction company M, the extra cost due to fuel loss is also \$100m (100%).

Example 2: In C-system, the imbalance due to traction load is 25% and the traction load is 1% of total 6000MW load. Calculate the loss (in MW and %) due to the ac traction.

Solution: 1% load is 60MW, and 25% loss is 15MW, i.e. 0.25% of 6000MW. For each \$100m electricity sale to traction company M, the extra cost due to fuel loss is \$25m (25%).

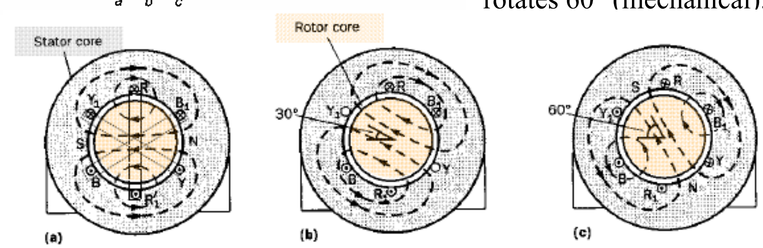
In both cases, the increases in fuel cost (unduly regarded as reduction of generator efficiency) are paid by all customers in the system. However, unlike other generator losses, this 'loss' due to imbalance can be eliminated/reduced.

Rotating Field of 3-ph Machine



The stator balanced current I_1 establishes a field rotating clockwise (i.e. forward).

As the stator current advanced 60° (electrical), the stator field F_1 rotates 60° (mechanical).

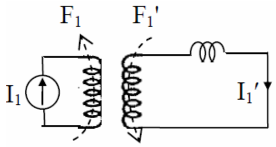


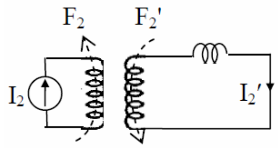
Distribution of magnetic flux due to 3-phase current (using right-hand rule)

The stator field F_1 induces I_1' in rotor windings which establishes another field F_1' (not shown in the above diagram).

Rotating Field and Motor Torque

The balanced 3-ph current I_1 at stator winding establishes a rotating field F_1 which induces I_1' in rotor winding. I_1' will establish anther rotating field F_1' in synchronism with F_1 (i.e. F_1 and F_1' are of equal speed).
The reaction of F_1 and F_1' will provide a forward torque τ_1.





Likewise, the unbalanced stator current I_2 will induce I_2' in rotor. I_2 and I_2' will establish its own field. Both F_2 and F_2' rotate in backward direction and are in synchronism. Their reaction will create a negative (backward) torque τ_2, opposing τ_1.

In general [6], $\tau_1:\tau_2 = (I_1')^2/(1-N) : (I_2')^2/(1+N)$ where N=per unit motor speed.

For 1-ph motor, at motor standstill (i.e. N=0), stator current $I_1=I_2$ and rotor current $I_1'=I_2'$. $\therefore \tau_1=\tau_2$ and motor cannot self-start. Thus, all domestic appliances (e.g. fan) must install compensation winding to start the motor.

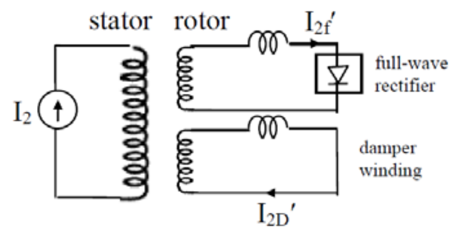
Rotating Field and Generator Torque (1)

Under no load, the generator drive has to provide a small torque τ_0 for constant losses (e.g. windage, friction, & iron losses).

For balanced 3-ph load, additional torque τ_1 is required to supply the electrical power ($\tau_1 N=\sqrt{3}VI\cos\phi$). Total torque is $\tau=\tau_0+\tau_1$.

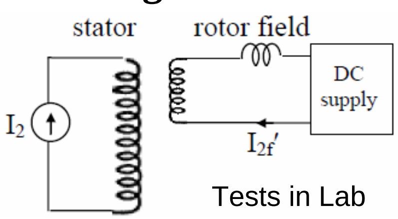
For unbalanced load, stator I_2 produces a backward rotating field, and the torque is increased to $\tau=\tau_0+\tau_1+\tau_2$.

The rotor has two separate windings. τ_2 is mainly due to the double frequency current I_{2D}' in the damper winding.



Because the damper winding are thick and short-circuited bars, the induced I_{2D}' is very large. A much smaller I_{2f}' of double frequency is also induced in the rotor field winding, but the current magnitude is restricted by the path of full wave rectifier in the brushless excitation system.

Rotating Field and Generator Torque (2)



Tests in Lab

Experiments had been carried out in Machine Lab of PolyU on a 2kVA synchronous generator. Because the machine is small rating, it has no damper winding, $I_{2D}'=0$ and $I_{2f}'=0.12A$ is very small. But $\tau_2 \approx 0.07$ N-M is obtained in all different 3 tests.

The test results were endorsed by a renowned Professor in Electrical Engineering Dept. of HK City University, an expert in "Power Electronics & Machine Drive". He also agreed the concepts now presented in slides 32-35.
(Details had been discussed in [7].)

Recall that τ_2 is proportion to $(I_2')^2$, since speed N=1 for synchronous machine.
In torque analyses, the τ_1/τ_2 relative to stator current I_1/I_2 is crucial, rather than to the rotor current I_1'/I_2'. However, without the damper winding data nor any machine parameters, the exact relation between τ_1/τ_2 and I_1/I_2 for large rating machines cannot be obtained.

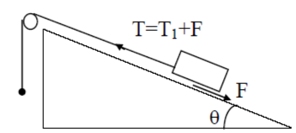
Since I_{2D}' is very large, it is likely $\tau_2>\tau_1$ in the extreme case of $I_1=I_2$.

In the following, a conservative relationship $\tau_1/\tau_2=I_1/I_2$ is assumed.

Energy Loss with Friction

Frictional loss in linear motion

Consider a mass M pulled up along a rough slope. The total tension is $T=T_1+F$, where $T_1=Mg.\sin\theta$ and F is frictional force opposing the motion. The energy to pull the mass is increased due to Friction.



The extra energy will be dissipated as heat generated by friction.
If the slope is very rough, the heat may cause damage to the mass.

If a generator has unbalanced loading, extra energy is required to overcome the negative torque. This energy will be dissipated as iron losses (eddy current and hysteresis), causing severe damage to the rotor [2]. 37

To protect the generator from the severe damage, the generator will trip if current imbalance exceeds a certain limit. (In CLPP, the limit is 5%.)

The extra energy input reduces the generation efficiency. Very often it is regarded as generator loss.

Impact of Damper Winding Current to Rotor [1,2]

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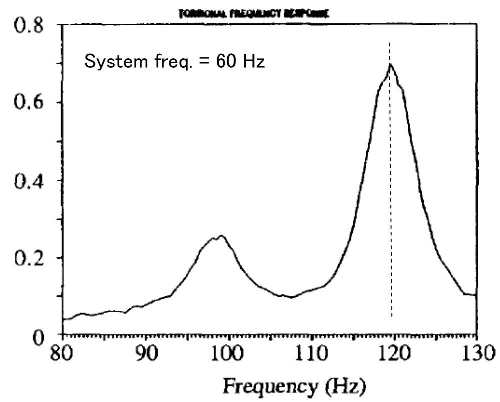
The damper current I_{2D}' is similar to the positive sequence current, except that the resulting reaction field rotates counter to the dc field system and hence produces a flux which cuts the rotor at twice the rotational velocity, thereby inducing double frequency currents in the field system and in the rotor body, creating additional hysteresis loss P_h and eddy current loss P_e. In general, both $P_h=k_h f B_m^{\,x}$ and $P_e=k_e f^2 B_m^{\,2}$ will increase with the frequency f.

The resulting eddy-currents (proportional to f^2) are very large and cause severe heating of the rotor. So severe is this effect that a single-phase load equal to the normal 3-phase rated current can quickly heat the brass rotor slot wedges to the softening point; they may then be extruded under centrifugal force until they stand above the rotor surface, when it is possible that they may strike the stator iron. Overheating of the wedges may be sufficient to anneal them enough to result in rupture in shear. Concentration of heating occurs on portions of the coil binding rings and here surface fusion has been known to occur.

I_2 Impact: Super-synchronous Resonance to Turbine Blade [2]

Other than the above well known adverse effects, turbine blade super-synchronous resonance is one of the most serious problems. The severity of negative sequence current problems resurfaced after the turbine blades of a nuclear power plant in a country of Southeast Asia were broken and almost caused a severe nuclear disaster.



It was because the double frequency component of I_2 may match the mechanical resonance of the turbine blades due to the frequency deviation and induce the supersynchronous resonance.

Impact of Current Imbalance to Energy Consumption

The negative sequence current I_2 creates a stator field (of double frequency $2f_0$) rotating in opposite direction to the rotor motion, which will downgrade generator performance and efficiency, overheat the rotor. For a total generation of, say 6000MW, a very slight increase of, say, 0.1% generator output (e.g. to cover the additional losses) represents an undue increase of 6MW.

If a system generation is equally shared by nuclear, gas and coal, the overall generation efficiency roughly equals to (0.33+0.55+0.35)/3=0.41, and the increase of rate of fuel waste will be amounted to 6/0.41=14.6MW. This extra increase of fuel cost will be shared by all consumers at large.

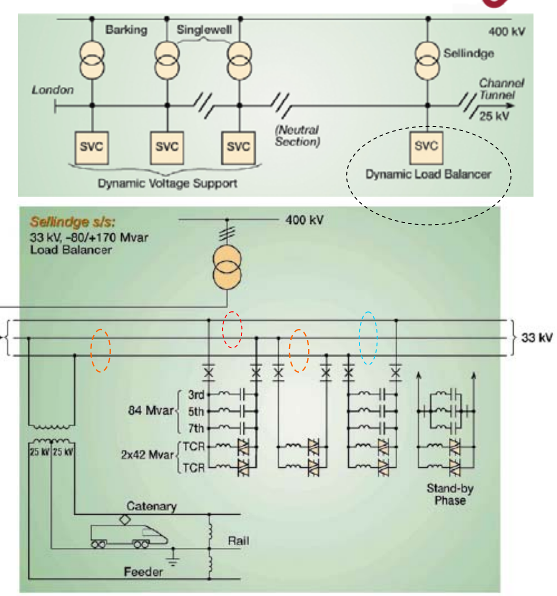
Usually, the ac traction load is a small fraction of the total system generation and a small percentage decrease in generator efficiency may not be noticeable. For instance, in 2009, the CLPP demand is 6389MW and the 30-minute average peak demand of KCR is about 64MW.

Case studies here are based on simplified assumptions/data of KCR. Without the CLPP generator parameters and the realistic imbalance data, it is impossible to estimate the actual energy waste due to the traction imbalance.

Combating Imbalance by 33kV Dynamic Load Balancer [5]

Installed at high-speed rail of Channel Tunnel Rail Link at Sellindge s/s near Dover.
Rail length 109 km between London and Paris.
Total time travel: 2hr 20min.

(HK-GZ 150-km within 2hr.)



The Balancer is regarded as an asymmetrical controlled stator var compensator (SVC).

The Balancer is controlled to compensate I_2 drawn from 400kV and to regulate power factor to unity.

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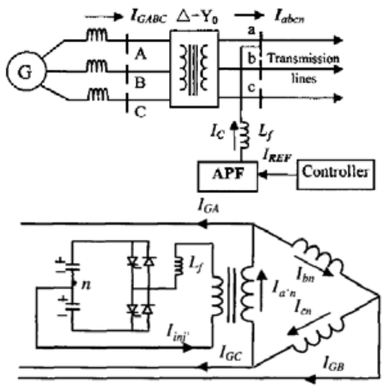
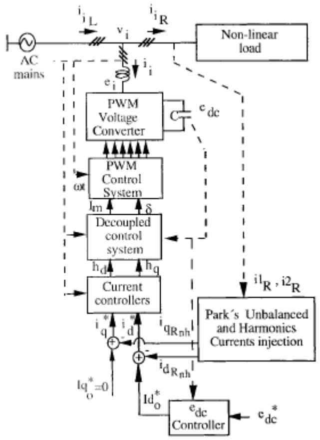
Combat Imbalance by Active Power Filter [2]

Active power filter based on voltage source inverter



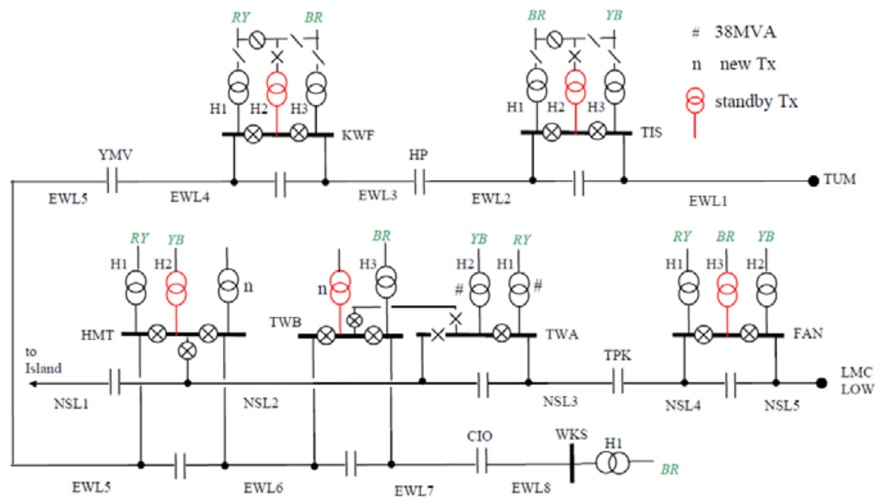
Active power filter with unbalance current control



However, all these combating methods are complicated, and installation/operation costs are very high.

Design Proposal at 2011 for future KCR with SCL

As mentioned, ERL will be extended to Island, to form the North South Line (NSL). WRL and MOL will be combined/extended to form the East West Line (EWL).



NSL (the dominant line in KCR) has 5 sections with a total length of 42.81km.

Some Features of NSL

Section	NSL1 -	NSL2 -	NSL3 (ERL2)	NSL4 (ERL3)	NSL5 (ERL4)	Total
kM	2.41	13.7	10.3	7.8	8.6	42.81
Tx MVA	?	38	38	26.5	26.5	

The length of EWL is 58.9km. If the length of Express Rail is 26km [8], the total length of KCR will be 36.7+60.15+2=127.71km, and the 2.41km NSL1 (less than 2% length of KCR) is to be supplied by HEC.

'25kV system is commonly used for sub-urban and high speed trains only in the international market', so this short ac line NSL1 of one section is permanent in HEC. Passengers from Kowloon, NT or Guangdong province can make transition to other spots via 5 other rail lines (all 1.5kV dc) at Admiralty/Central passenger stations. Only a layman will believe ac line will be extended (underground) on Island side.

Passengers of NSL and EWL can make transition at Hung Hom station (HUH) at NSL2. Thus, NSL2 (the longest section in NSL) will have much higher loading than that of NSL3, in particular during morning/evening, when most people will come-to or leave offices at Central, Wanchai and Causeway Bay (CWB).

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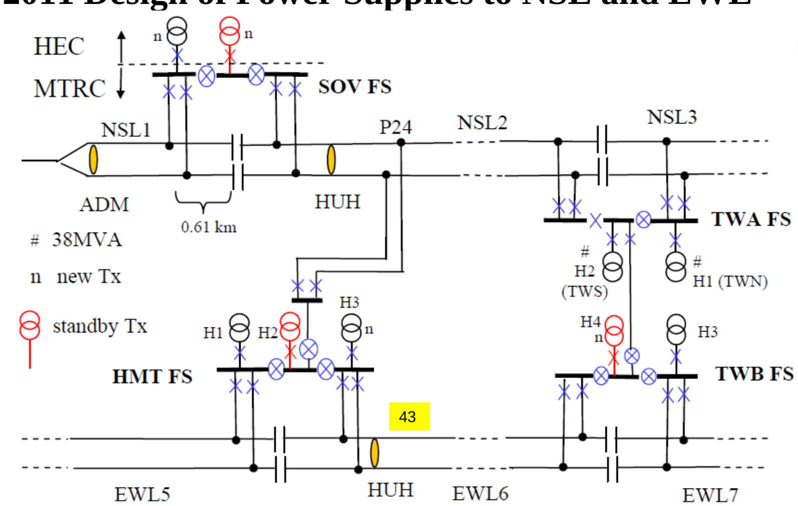
In 2009, the loading of ERL2 (NSL3) already exceeded 26.5MVA. Ten years later with SCL, NSL3 loading should be increased. NSL2 (33% longer than NSL3 and with HUH interchange) must have even higher loading. If one says the computer simulation shows that the NSL2 loading is within 26.5MVA, please change the software.

2011 Design of Power Supplies to NSL and EWL



In 2009, 26.5MVA #H1 supplying ERL2 (NSL3 in SCL) was upgraded to 38MVA due to overload. For train supply security, the standby #H2 was also upgraded to 38MVA. It is expected for the same security reason, a proper SCL design at least fulfils that all standby Tx must be capable to fully backup the loss of any on-load Tx supply.

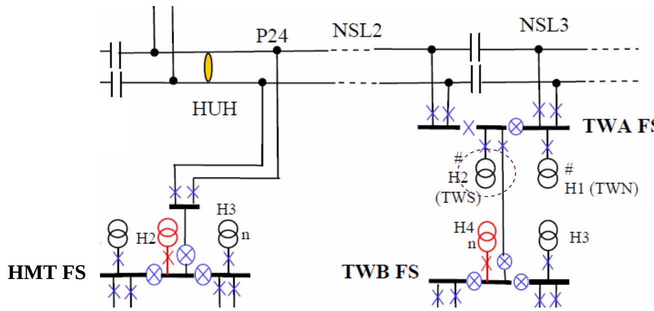
Supply Security under Loss of 38MVA Tx H2

In the SCL design 2011, at TWA, the 38MVA #H2 (put to standby since 2009) will supply NSL2, the section with most heaviest load in KCR.

But the new standby H4 at TWB is of only 26.5MVA rating [9].

In fact, NSL2 has a second standby H2 at HMT FS, but this Tx is also of 26.5MVA rating.

Thus, under loss of #H2 at TWA, the train service of the most critical line NSL2 must be degraded, which will affect entire NSL as well as transits from EWL.



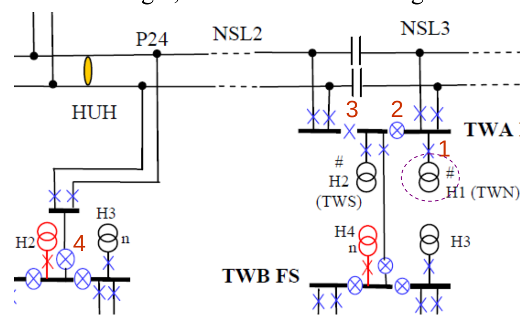
Since the critical section (NSL2) has to degrade service, is the Design proper?

Supply Security under Loss of 38MVA Tx H1

Under loss of H1, the standby Tx H4 at TWB has to connect to the same bus of #H2. Because #H2 & H4 are of different 132kV source (SHE32 & CWS132) and of different MVA rating (38 & 26.5)[9], parallel Tx operation is strictly not permitted.

A M-engineer claimed that #H2 can recover NSL3 supply, using standby H2 at HMT to supply NSL2 , based on 4 switching.

First, opening 1 to isolate faulty H1. But
After closing 2, #H2 has to supply both NSL2 and NSL3, degrading 2 line services.
After opening 3, NSL2 temporarily loses supply, i.e. no train service.
After closing 4, NSL2 train service degraded due to inadequate rating of standby H2.



It is very strange that backup comes from a remote standby Tx, instead from local Tx H4. (Coupling of TWA and TWB is useless in this scenario.)

A simple solution is to relocate #H2 to the side bus at TWA, although inadequate standby Tx rating remains unsolved.

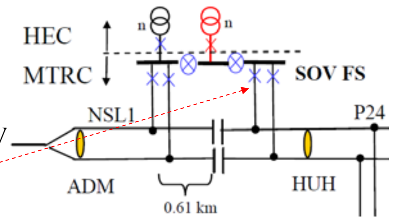
To use 'remote-water' for 'self-fire' and affecting neighbor, is the Design proper?

Supply to NSL1 at Island by HEC

As mentioned, the single section (NSL1) at Island will be permanent in HEC. It is unfair to HEC to supply only a short section (2.41km) but to offer two Tx, according the 2011 SCL design.

In the existing ERL system, each line section must have at least one 25kV passive harmonic filter. (Filter cannot be installed in WRL because the SP1900 train in WRL is of unity power factor [3,4].) It seems a filter has been missed in the 2011 design. For only 1 section, a balancer may be needed at NSL1.

Accordance to the CLPP practice that each KCR supply requires two s/s, the supply to NSL1 needs one HEC 132kV FS to house the 132/25kV Tx, and one KCR 25kV FS to house the three 25kV bus sections, eight 25kV CB and the filter, plus 0.61km 25kV cables connecting neutral section (in tunnel) and the SOV FS (on land).
Thus, the components for the FS on Island are quite bulky, even though this KCR section is very short.



South Ventilation Building (SOV) is at sea-front of Causeway Bay (CWB).

Land Shortage Problem at CWB & Solution

Land in Causeway Bay (CWB) is 'scarce' and very expensive. A pragmatic and cost-effective rectification is proposed here that no extra FS is needed in CWB. It is based on the fact that the NSL1 (less than 2% of KCR) at Island can be easily absorbed by CLPP, which is beneficial to CLPP, HEC and their customers, in particular to those customers at CWB.

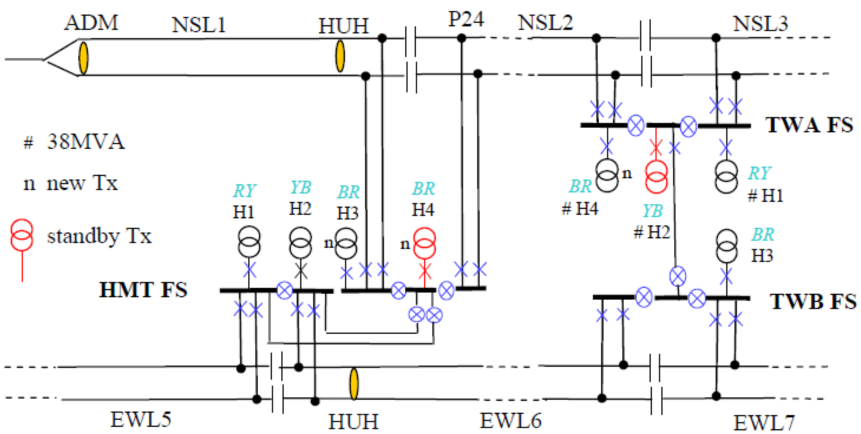
With NSL1 supplied by CLPP, the neutral section (original design located in tunnel) is then shifted to Kowloon, and NSL1 will be supplied by HMT FS. This shift increases the length of the very short NSL1 and reduces the longest NSL2. Thus, Tx load burden to NSL2 during peak-hour is much alleviated.

	Section	NSL1	NSL2	NSL3	NSL4	NSL5
Original	kM	**2.41**	**13.7**	10.3	7.8	8.6
	Tx MVA	?	38	38	26.5	26.5
Revised	kM	**5.71**	**10.4**	10.3	7.8	8.6
	Tx MVA	26.5	38	38	26.5	26.5

NSL2 will be supplied by a new 38MVA Tx #H4 in TWA, such that 38MVA #H2 can fully utilize the interconnector of TWA & TWB, to backup 4 KCR sections: NSL2, NSL3, EWL6 & EWL7.

More Proper & Reliable SCL Design

Likewise, HMT FS bus layout is revised such that the standby H4 can backup 4 KCR sections: EWL5, EWL6, NSL1 & NSL2. Although H4 at HMT is of 26.5 MVA and is unable to resume full service of NSL2, it is regarded as auxiliary backup to NSL2 and the 26.5 MVA rating is adequate for double contingency.



Comparison of Design Economies

The revised design will enable the two standby Tx to backup 4 sections each, and the train service will not be degraded after power restoration. Such security enhancements in both HMT and TWA/B will increase the 25kV components. However, the component increases are still less than that of the original because one additional CLPP Tx can replace two substations (132kV and 25kV) at South Ventilation Building (SOV) in CWB.

Original	SOV	HMT	TWA	TWB	Total
Tx	2	3	2	2	9
CB	8	12	9	9	38
Section	3	4	3	3	13

Revised	SOV	HMT	TWA	TWB	Total
Tx	0	4	3	1	8
CB	0	17	10	8	35
Section	0	5	3	3	11

For simplicity, the costs of 132kV CB/isolator for each Tx, the filter (and balancer) in SOV, the land/building costs for two stations (HEC 132kV and MTR 25kV) on Island are skipped.

A M-Engineer informed that tunnels needs ventilation, and the 25kV FS may use SOV (also under MTRC) to save land cost, but this save is not for HEC 132kV s/s. Can the SOV be also moved to Hung Hom (with cheaper land cost) if no FS is needed on the Island?

The above is for the one-off installation cost which becomes minor as compared to the giant increase in the fuel cost (due to imbalance) and the environment cost, both are for long term.

Reducing Imbalance Impact for SCL Design

ERL is always the dominant line in KCR (i.e. much higher Tx loading than that of WRL and MOL [1]). With SCL, the dominant line should be the NSL, but the abnormality continues in the 2011 Design, case (c). To eliminate the abnormality and to reduce the imbalance, it is imperative to resume the three types of phase connection in the coming NSL, case (d).

Phase connections of ERL and the subsequent NSL (in CLPP system only)

Cases	NSL1	ERL1 or NSL2	ERL2 or NSL3	ERL3 or NSL4	ERL4 or NSL5
(a) From 80's to 2004		*BR*	*RY*	*RY*	*YB*
(b) Since phase-swap at 2004		*YB*	*RY*	*RY*	*YB*
(c) Proposed 2011 design	*(HEC)*	*YB*	*RY*	*RY*	*YB*
(d) Revised	*BR*	*BR*	*RY*	*RY*	*YB*

Suggest NSL2 to be supplied by a new ***BR*** Tx (38MVA) at TWA, and NSL1 will be ***BR***, same as NSL2. As a result, NSL has 2 ***BR***, 2 ***RY*** and 1 ***YB***, and the abnormal design of only 2 types of phase connection in the dominate rail in KCR (since 2004) no longer exists.

In the revised design, HEC is most benefited since the 100% imbalance is completely removed. CLP is also benefited that HMT FS has 3 Tx of 3 difference phases, and the load is almost perfectly balanced. However, the overall imbalance at CLPP is most vital as it will affect the generator fuel loss.

Relative Tx loading of NSL and EWL

Based on the similar system parameters and using the same assumption that Tx load is proportional to number of car in a section, and each section in the same line has equal loading, the relative loading of NSL and EWL (in CLPP systems only) can be estimated:

KCR system parameters at peak load for 2011 SCL Design

System	Car	Length (km)	Headway (min)	Section	Load Ratio Tx	Load Ratio System
NSL	12	40.4	2.5	4	1.0	4
EWL	7	58.9	3	8	0.354	2.83

KCR system parameters at peak load for revised Design

System	Car	Length (km)	Headway (min)	Section	Load Ratio Tx	Load Ratio System
NSL	12	42.8	2.5	5	1.0	5
EWL	7	58.9	3	8	0.418	3.34

As mentioned, the Tx loading is affected by the number passengers in a car. With a conservative assumption that passenger/car of the NSL is twice of that of EWL, the Tx load ratio of NSL:EWL is 1:0.177 for original 2011 Design, and 1:0.209 for the revised design.

Imbalance Estimations

Based on the Tx load ratio of 1:0.177 and 1:0.209, the imbalance can be estimated:

Tx loading and imbalance in KCR system with 2011 Design

Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	H1[1]	H2 [1]	
Tai Wai	H1[1],	H2 [1]	H3 [0.177]
Ho Man Tin	H1 [0.177]		H3 [0.177]
Wu Kai Sai		H1 [0.177]	
Kwai Fong	H1 [0.177]		H3 [0.177]
Tin Shui Wai		H3 [0.177]	H1 [0.177]
Current Imbalance	NSL [2-2-0]		50%
	EWL [0.354-0.354-0.708]		25%
	Overall [2.354-2.354-0.708]		30.4%

(4-4-4 is allocated to 12 CLPP Tx but imbalance is high.)

Tx loading and imbalance in KCR system with revised Design

Substation	Tx primary phase connection and loading		
	R-Y	*Y-B*	*B-R*
Fanling	H1[1]	H2 [1]	
Tai Wai	H1[1]		H2[1],H3[0.209]
Ho Man Tin	H1 [0.209]	H2 [0.209]	H3 [1]
WKS		H1 [0.209]	
Kwai Fong	H1 [0.209]		H3 [0.209]
Tin Shui Wai		H3 [0.209]	H1 [0.209]
Current Imbalance	NSL [2-1-2]		20%
	EWL [0.418-0.627-0.627]		12.5%
	Overall [2.418-1.627-2.627]		13.7%

In the revised design, imbalances of NSL and EWL are much reduced. The overall current imbalance at generator is reduced by (30.4-13.7)/30.4=55%.

Further reduction of imbalance can be achieved by Tx re-phasing.
A more pragmatic method is by careful design for the coming Express Rail.

Conclusion (1)

Imbalance of 1-ph traction load to 3-ph power system is inevitable. The major impact is the increase of generator loss (small in %, but large in magnitude and is long-term).This impact will be diminished with more rail sections with ac traction development.
However, due to the abnormal phase-swap in 2004, the imbalance in CLPP was increased and train supply security was impaired.

In 2010, the speaker submitted a paper on Imbalance Impact to HKIE and delivered a seminar on same topic. After the seminar, the speaker had 'privately' discussed with power utility engineers, explaining to him that the imbalance impact can be reduced by proper re-phasing. But the discussion was of no-use.

With limited but genuine data obtained in 2011, the speaker found that the imbalance became worse in the proposed SCL design. In particular, the single section at Island will produce 100% imbalance and this effect is permanent, irrespective of the development of Express Rail nor any future ac traction development.

Conclusion (2)

Recently, SAR invited public consultation on SCR [10]. As a scholar, the speaker determined to deliver this seminar for public open discussion. (Closed-door discussion is no longer useful.)

Based on the 2011 Design of SCL, it is observed that:

1) Standby Tx cannot fully backup the loss of any one on-load Tx in <u>two</u> NSL sections, and train services must be degraded.
2) NSL is the dominant line of KCR, but the abnormality of having only 2 types of phase connections remained.
3) One section (NSL2) which houses the interchange passenger HUH station is particularly long with extremely high load burden.
4) HEC has to feed a very short section (less than 2% of total KCR) with quite bulky design of two substations and 600m cables connected to the tunnel neutral section.
5) The only one section on Island will result in giant fuel energy loss. This loss is permanent since the ac line for intercity service will only terminate at Admiralty of Central and the SCL any ac link will not have extension on a small island where Admiralty has numerous traffic facilities.

Conclusion (3)

The revised proposal presented in the seminar has the following merits.
a) One Tx in an existing CLPP 132kV s/s suffices to replace two s/s (132kV and 25kV) on the Island, reducing the installation cost as well as the very expensive land cost at Causeway Bay.
b) The 100% and permanent imbalance at HEC due to traction will be completely removed, the generator loss is also removed, and the power quality problem (due to ac traction) to the HEC customers at Causeway Bay is also removed.
c) The imbalance of CLPP system due to ac traction will be reduced by 55%, also resulting in a great reduction of fuel loss (long term).
d) Since the southern part of NSL is more crucial, two standby Tx are slightly modified such that each Tx can backup four rail sections. Degraded train service will not occur under single contingency of Tx loss.
e) The very short NSL1 is lengthened, the very long NSL2 is shortened, and these two Tx loadings are more evenly shared. ,

The proposed design should be beneficial to MTRC, CLPP, HEC and all HK citizens.

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About the Speaker

Dr. C.T. Tse was the Associate Professor in the Electrical Engineering Department, the Hong Kong Polytechnic University (PolyU). Before joining the Hong Kong Polytechnic in 1990, Mr. Tse was the Planning Engineer of System Planning Branch in CLP. His main duty was to look after power system stability and the 'abnormal' loads, such as arc furnace and traction. During his 22-year service in PolyU, Dr. Tse has engaged in 7 consultancy investigations associated traction power supply (3 with KCR, 2 with MTR, one with earthing study of SCL and one overseas 1.5kV DC project). One of his research works was supported by MTRC via the PolyU Teaching Company Scheme. As the Visiting Associate Professor with the EE Dept after retirement since September 2010, three of his taught MSc subjects are associated with traction systems. Recently he published a HKIE transaction paper [1] and delivered 2 HKIE/IEEE seminars [2,3], all related to AC traction supply in HK

In response to the recent Public Consultation of SAR [10], the seminar is jointly organized by The IEEE-HK Joint Chapter of PES/IAS/PELS/IES, The Institute of Measurement & Control (HK) and the IEEE Power Electronics Society, and is supported by The Hong Kong Polytechnic University Staff Association.

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The materials presented in the seminar may contain confidential or privileged information derived from his research channels and are solely intended for reflecting his views on academic grounds and arousing response on public interest basis to the current call for comments on the project.