RESEARCH OF AN ACTIVE FILTER BASED BALANCED POWER SUPPLY SYSTEM FOR RAILWAY TRACTION

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ABSTRACT-This paper presents a balanced 3/1 supply scheme for electric railway. By employing an active filter, the current of the three-phrase delivery system is balanced while the load is single phrase, which makes it possible for the traction system to behave like a pure-resistance load, with unity power factor and no harmonics. Simulation results are present to verify the scheme's topology and control strategies.

1. INTRODUCTION

Single-phrase supply system is widely used in the electrified railway. It has the advantages such as low cost, easy implementation and maintenance over three-phrase system. As a single phrase sub-system of the three-phrase power delivery system, although special methods have been taken to keep the load of three phrases balanced viewing from the interface between the two systems, it is impossible to get balance effect because of the randomness of the load and its distribution. This unbalance results in a large negative sequence current to the three-phrase system and does great harm to it.

Electrical locomotives can be considered to be an inductive load and produce great reactive power to the supply system. Passive reactive filter and static compensator has been employed to inject reactive power needed by the locomotives. As power electric devices widely be used in the AC/DC, AC/DC/AC, AC/AC trains, the harmonics it generated will pollute the supply system and affect communication system if counter measures are not taken.

This paper proposes a electrified railway supply system topology, using a three-phrase active filter to compensate the negative sequence current, reactive power and harmonics produced by locomotives. View from the power supply system side, the electrical traction system will act as a balanced resistance load.

2. TOPOLOGY OF THE PROPOSED SUPPLY SYSTEM

Traditional electrified railway supply system uses the phrase rotation technique as shown in Fig.1. Each traction substation(SS) is consisted mainly of a transformer, which turns the voltage of the three-phrase power system into the proper voltage level, usually from 110kv to 25kv, and delivers it to two feeding sections, each of single phrase. In order to maintain the three-phrase power system's balance, sections alone the railway must be rotated from phrase a to b, b to c, and c to a, etc.

The existing system has the following disadvantages:

1) The balancing effect exists only when sections of every phrase have the same load, but this is apparently almost impossible, since the load and its distribution is random.

2) When a train run from one section to another, it must perform a series of operation such as putting down its bow collector or break off its main switch, this restrict the train's speed, especially in the high speed railway system.

3) As locomotive is always an inductive load, and electric converters are widely used, additional power compensator and harmonic filter must be installed to elevate the power factor, eliminate the harmonics.

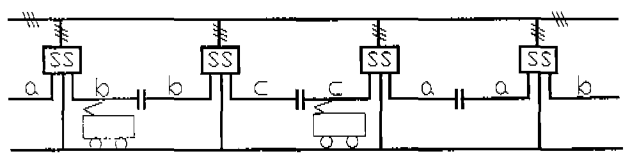

Fig.1 Traditional electrified railway supply system

In the proposed system shown in Fig.2, every substation(SS) has a transformer and an active power filter(APF). The function of APF is to output a single phrase current while the balance of its three-phrase input current maintained. At the same time, the load's reactive and harmonic current is compensated. This makes it possible for the traction system to act as a balanced three-phrase resistant load to the power delivery system.

As all the SS output the same phrase, here indicated by phrase-a, little care will be taken when a train passes the section insulator. The effect of the purposed system is unity power factor, no negative sequence current, no reactive and harmonic current, balanced load among three phrase while the load is actually unbalanced.

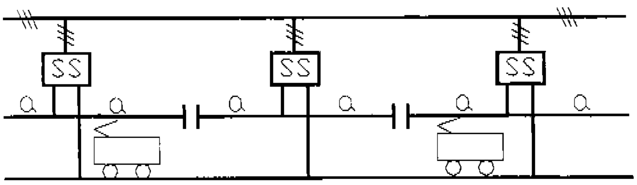

Fig.2 Proposed electrified railway supply system

3. CONTROL STRATEGY OF THE PROPOSED ACTIVE POWER FILTER

Principle of the proposed APF

The configuration of the proposed APF is shown in Fig.3.

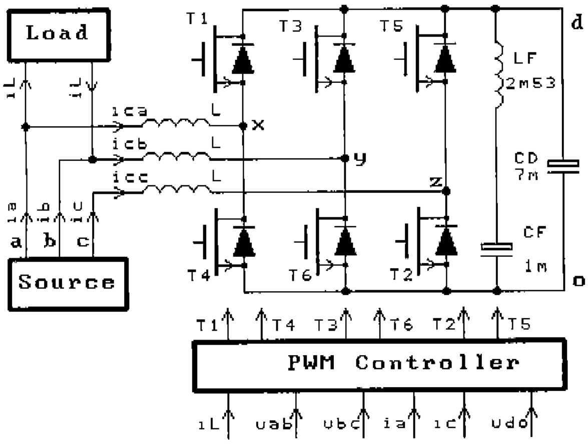

Fig.3 configuration of the APF circuit

Assume that

$$\begin{cases} \mathbf{I_s} = [i_a, i_b, i_c]^T \\ \mathbf{I_c} = [i_{ca}, i_{cb}, i_{cc}]^T \\ \mathbf{I_l} = [i_{la}, i_{lb}, i_{lc}]^T \end{cases} \quad (1)$$

Form Fig.3 , it can be found that

$$\mathbf{I_c} = \mathbf{I_s} - \mathbf{I_l} \quad (2)$$

and

$$\mathbf{I_l} = [i_L, -i_L, 0]^T \quad (3)$$

If the source's reference current $\mathbf{I}_{sr}$ can be figured out , which consists of only fundamental sine-wave and in-phrase with the supply's voltage, and the load's current is known, then, the compensator's reference current $\mathbf{I}_{cr}$ can be calculated through (2). By controlling **Ic** to trace $\mathbf{I}_{cr}$,which is performed by the PWM controller, the source only supply the balanced, fundamental current, which is what the target means.

Algorithm design

As discussed above, we must try to calculate i_{sr} in order to control APF. Assuming

$$\begin{cases} u_a(t) = U_m \sin wt \\ u_b(t) = U_m \sin(wt - 120) \\ u_c(t) = U_m \sin(wt - 240) \end{cases} \quad (4)$$

$$\begin{cases} i_{ar}(t) = I_m \sin wt \\ i_{br}(t) = I_m \sin(wt - 120) \\ i_{cr}(t) = I_m \sin(wt - 240) \end{cases} \quad (5)$$

$$i_L(t) = I_{1L} \sin(wt + \varphi_1 + 30) + \sum_{n=3}^{+\infty} I_{nL} \sin(nwt + \varphi_n) \quad (6)$$

The single phrase load's instantaneous power can be given by

$$p_L(t) = i_L(t) \times u_{ab}(t) \quad (7)$$

while

$$u_{ab}(t) = \sqrt{3} U_m \sin(wt + 30) \quad (8)$$

Form (6),(8), $p_L(t)$ can be written as

$$p_L(t) = \frac{\sqrt{3}}{2} U_m I_{1L} \cos\varphi_0 + q(t) + h(t) \quad (9)$$

q(t) is the instantaneous reactive power, and h(t) is the instantaneous harmonic power, which is given by:

$$q(t) = \frac{\sqrt{3}}{2} U_m [I_{3L} \cos(wt + \varphi_3 - 30) - I_{1L} \cos(2wt + \varphi_1 + 60)] \quad (10)$$

$$h(t) = \frac{\sqrt{3}}{2} U_m \sum_{3}^{+\infty} I_{nL} \sin(wt + 30) \sin(nwt + \varphi_n) - \frac{\sqrt{3}}{2} U_m I_{3L} \cos(wt + \varphi_3 - 30) \quad (11)$$

Load's average active power is

$$P_L = \frac{1}{T} \int_0^T i_L(t) u_{ab}(t) dt = \frac{\sqrt{3}}{2} U_m I_{1L} \cos\varphi_0 \quad (12)$$

Assume that P_L is all supplied by source,

$$u_a(t) i_{ar}(t) + u_b(t) i_{br}(t) + u_c(t) i_{cr}(t) = P_L \quad (13)$$

from (4) ,(5) and (13), Im is written as

$$I_m = 2P_L / (3U_m) \quad (14)$$

By introducing

$$K = 2P_L / (3U_m^2) \quad (15)$$

and considering (4), (5) can be written as

$$\begin{cases} i_{ar}(t) = K u_a(t) \\ i_{br}(t) = K u_b(t) \\ i_{cr}(t) = K u_c(t) \end{cases} \quad (16)$$

The control strategy

The control target is to ensure the source supplies a balanced current given by (16). To do this, APF must supply the current $\mathbf{I}_c$ given by (2), or rewritten as:

$$\begin{cases} i_{car}(t) = i_{ar}(t) - i_L(t) \\ i_{cbr}(t) = i_{br}(t) + i_L(t) \\ i_{ccr}(t) = i_{cr}(t) \end{cases} \quad (17)$$

The voltage at point x,y,z should be

$$\begin{cases} u_x(t) = u_a(t) - i_{ca}R_L - L\, di_{ca}/dt \\ u_y(t) = u_b(t) - i_{cb}R_L - L\, di_{cb}/dt \\ u_z(t) = u_c(t) - i_{cc}R_L - L\, di_{cc}/dt \end{cases} \quad (18)$$

The controller generate a group of bipolar triangle wave, u_{at}, u_{bt} and u_{ct}, which is synchronized to u_a, u_b and u_c correspondingly and the frequency is f_T, the magnitude is half of V_{REF} -- the reference voltage of the DC-side. Using following rule,

If ($u_x > u_{at}$) then set T_4 OFF and T_1 ON, else set T_1 OFF and T_4 ON;

If ($u_y > u_{bt}$) then set T_6 OFF and T_3 ON, else set T_3 OFF and T_6 ON;

If ($u_z > u_{ct}$) then set T_2 OFF and T_5 ON, else set T_5 OFF and T_2 ON.

we can control the APF efficiently.

4. SIMULATED RESULTS

Simulation on SABER has been done using the circuit of Fig.3 and the control strategy described above, while Um=1414v, L=3mH, R_L=0.1 Ω, Cd=7mF, L_F=2.533mH, C_F=1mF, V_{REF}=4000v, f_T=50×21Hz.

Two kinds of load have been simulated and the result of each is showed below.

Pure resistance load

$i_L = 300\sqrt{2}\sin(wt + 30)$, P_L=520KVA

Current of every phrase and their reference current are shown as Fig4. The transient wave-form is on the top, the stable on the bottom. Fig.5 is the spectrum of the source's current under stable state.

From Fig.4 and Fig.5, it can be seen that the source current is balanced , and the max. differentia of the source current is 5.63%, harmonics generated by APF is minute.

Inductive load with 3rd and 5th harmonics

$$i_L = 300\sqrt{2}\sin(wt - 6.87) + 45\sqrt{2}\sin(3wt) + 30\sqrt{2}\sin(3wt + 15) \quad (19)$$

cos_=0.8(lag)

Wave form of current is shown in Fig6; Current's spectrum is in Fig.7.

Even though the load's current contains a large ratio of harmonic and lags to voltage a angle of 30 degree, it can be seen from Fig.6 and Fig.7 that the wave-form of the compensated current is sine-wave with little harmonics, and in-phase with phrase-voltage. The max. differentia of the source current is 7.36%. This result proves that the proposed system not only can balance the source's output power while load is single-phrased, but also can compensate load's harmonic current and reactive power at the same time.

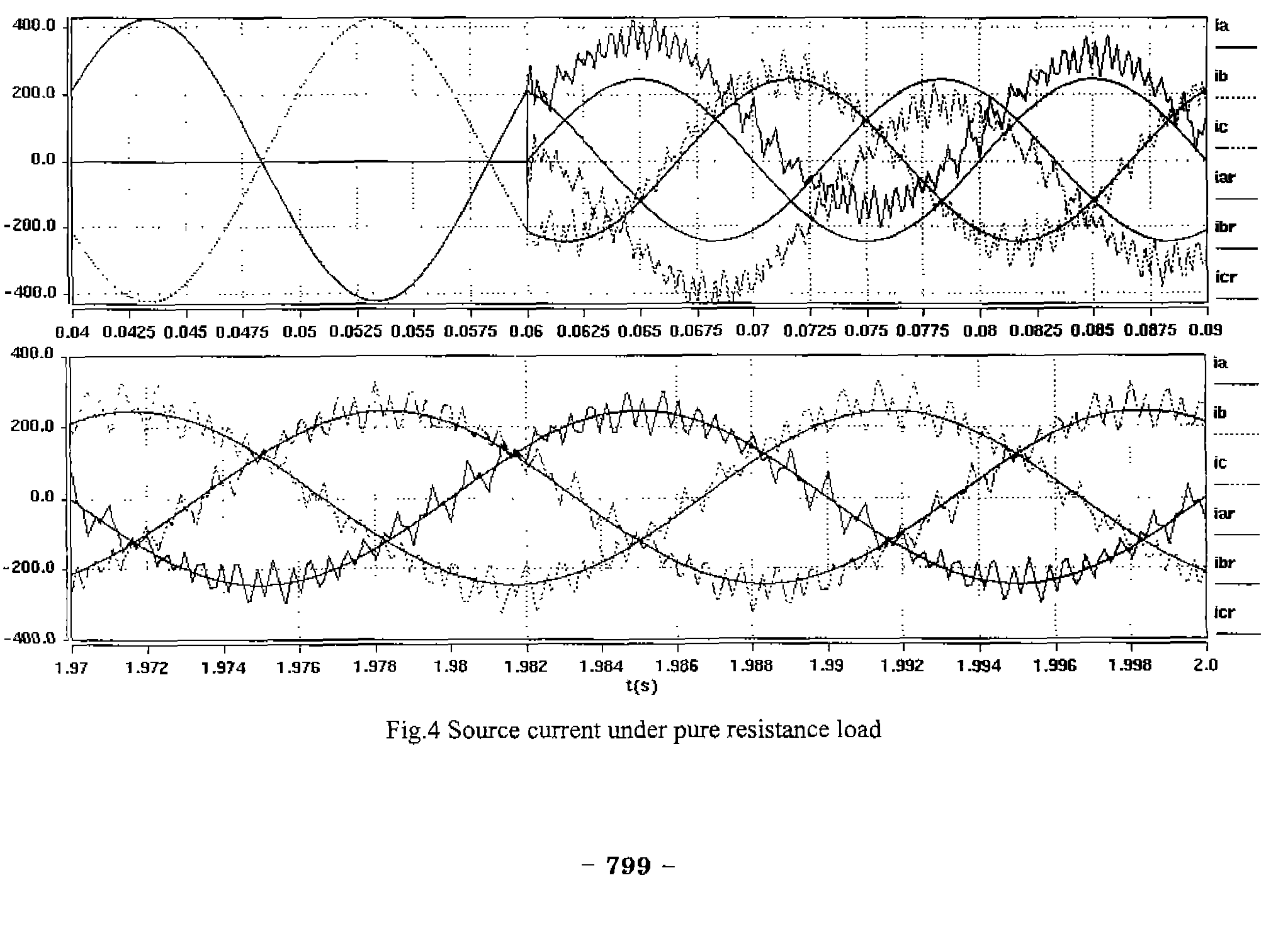

Fig.4 Source current under pure resistance load

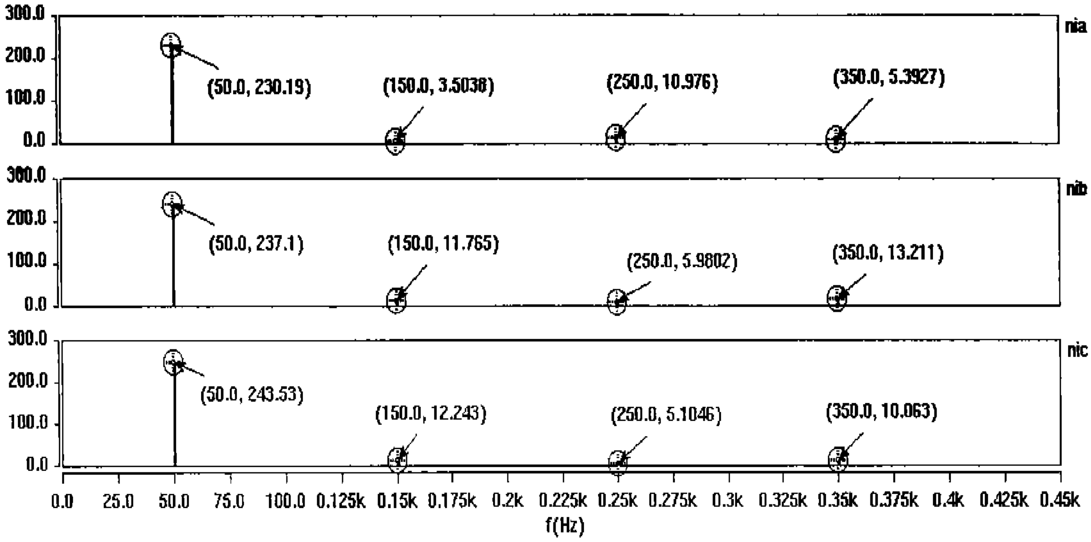

Fig.5 Spectrum of source current under pure resistance load

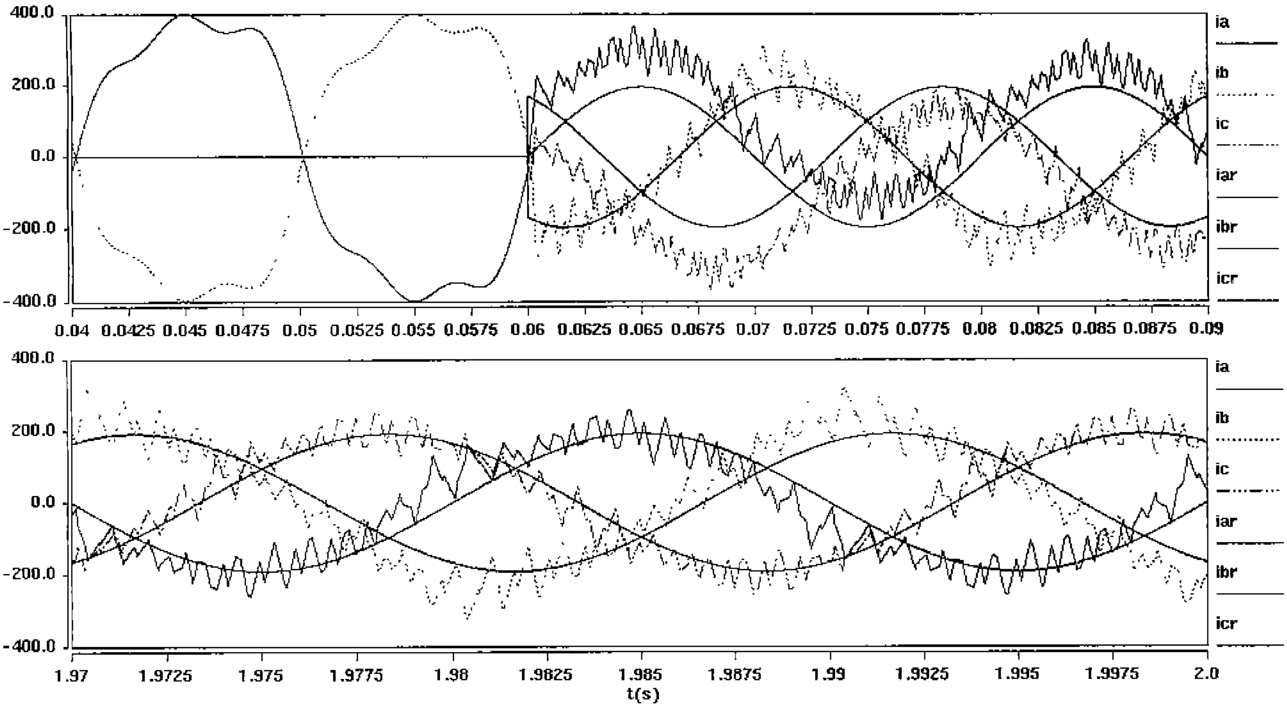

Fig.6 Source current under inductive and harmonic load

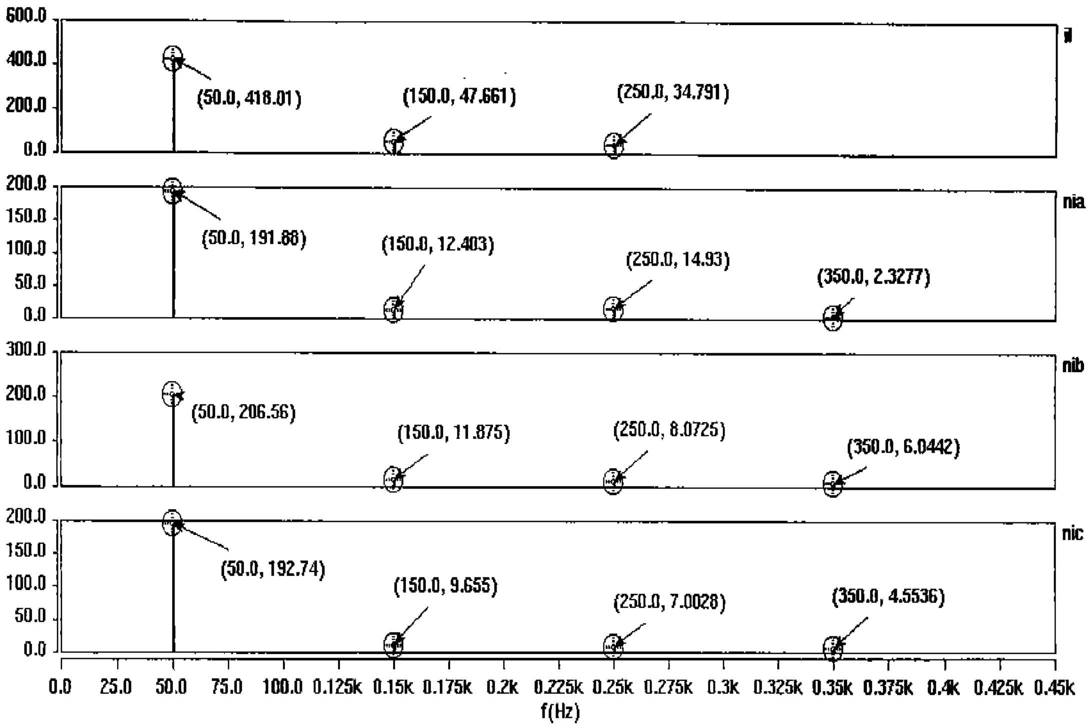

Fig.7 Spectrum of source current under inductive and harmonic load

5. CONCLUSIONS

The simulation results proved that the proposed traction supply system is effective to get a balanced effect to the power delivery system. The reactive power and harmonics generated by locomotives can be compensated at the same time, no additional filter is needed. A set of simulating device will be designed in a year to do further research.

6. REFERENCES

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