FUNDAMENTAL RESEARCH OF A NOVEL 3/1 PHASE CONVERTER FOR ELECTRIFIED RAILROAD

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Abstract Electrified railroads inject large amount of harmonics, negative sequence and reactive currents to electric supply systems. This paper introduces application of active filter as a 3/1 phase converter for electrified railroad. In this system active filter compensate harmonics, negative sequence and reactive currents and electric railroad and active filter together act as a balance three-phase load with power factor 1

1.INTRODUCTION

Because of many technical and economic benefits of three phase systems electrical energy in all of the power systems of the world is generated, transmitted and distributed with three phases. An ideal three-phase system must has many characteristics some of the most important characteristics are:

1- Voltages and currents of the system must have only a sinusoidal wave with nominal frequency of the system and they must not have any harmonics and dc component.

2- The voltages and currents of the three phase system must be balance that means zero and negative sequence components of voltage and current must be zero.

3- Reactive current occupy some part of system capacity and produce energy losses and volt drop in system, so in ideal power system power factor of the loads must be near the 1.

In these days number and length of electrified railway lines increase. Single-phase 50 Hz supply systems usually are used in new electric railways and new AC/DC/AC or old AC/DC locomotives work in these lines. Power electronic converters control speed and traction effort of electric locomotives these converters usually produce wide range of harmonics. Large capacity electric railroads are a large single-phase reactive load that has a lot of harmonics. These unbalance loads produce serious problems on harmonics, reactive power and negative sequence current of the system.

High pass filters usually are used for eliminating harmonics of the systems; these filters usually are made of passive elements such as reactor and capacitor

Rotary or static reactive current compensator can compensate reactive current. Synchronous condensers usually are used as the rotary compensator and reactor and capacitor can be used as the static compensator.

The existing balancing methods are [1,2]:

1- Use of the three phase to two phase transformers

2- Use of rotary balancing equipment such as synchronous condensers, induction motors to absorb negative sequence currents and their static counterparts that include switched capacitors and reactors

3- Use of three phase to single phase rotary or static converters to feed single-phase loads.

Mixed configuration of the mentioned methods must be used to improve all of the three main characteristics of the power system. Three phase to two phase transformer with capacitive reactive power compensator and LC high frequency filter usually are used in railway systems but this configuration can not improve characteristics up to standard level and result of their operation are related to power system construction and load characteristics.

Recently new method is developed to improve quality of the system. In this method an element that called active filter is add to the system to inject harmonics, reactive and negative sequence components of load current so supply system only fed active component of current. Active filter can absorb active power from one (or two) phase and inject to other phases so active filter can be used to improve some or all of the main characteristics of the system.

Basic principals of active filter were proposed around 1970. A lot of research has been done on active filter constructions, elements, control strategy and applications. Fast progress of the physics of electronic enables engineers to produce new power electronic elements. These new elements increase possibility of production of practical active filters.

Pulse width modulated (PWM) converter using insulated-gate bipolar transistor (IGBT) or gate-turn-off thyristor (GTO) generally operates as an active filter.

Active filters can be classified from their objectives, configuration, power circuit, and control strategy[3]. Respect to this classification for compensating of electrified railroad supply systems; shunt active filter can be used for compensation of electrified railroad loads.

This kind of active filter is similar to circuit that is used for ac motor drives, the difference is that active filter must act as nonsinusoidal unbalance current or voltage source.

Two types of power circuits are used for shunt active filters: Voltage source and current source PWM converter. Because of the higher efficiency and lower initial costs voltage source active filters are preferred to current source active filters. [3]

2.Analysis of the load current

There are mainly two methods for analyzing current of the load and extracting harmonics and negative sequence component. One is based on Furrier analysis and the other is based on the "d-q" theory. "d-q" theory usually is used for load current analysis [3]. "d-q" theory has two kind of application, at first application p_d and p_q (those are instantaneous active and reactive power) are calculated and analyzed to find active, reactive, positive, negative and harmonics components of the current. In this application power of the three phase are balanced, at second application direct and quadrature currents i_d and i_q are calculated directly then active and reactive, positive, negative and harmonics components of the current are found by analyzing of i_d and i_q. In this method currents of the phases are balanced, in this paper second application is used to make balance current in system.

Equation 1 shows currents of a three phase three wire system under nonlinear unbalance load, i_p and i_n respectively are magnitude of positive and negative currents and i_{ma} , i_{mb} and i_{mc} are harmonics order m of the currents of phases a, b and c. φ_p, φ_n, φ_{ma}, φ_{mb} and φ_{mc} are phase of the currents.

$$\begin{aligned} i_a &= i_p \sin(\omega t + \varphi_p) + i_n \sin(\omega t + \varphi_n) \\ &+ \sum i_{ma} \sin(m\omega t + \varphi_{ma}) \\ i_b &= i_p \sin(\omega t + \varphi_p - 120) + i_n \sin(\omega t + \varphi_n + 120) \\ &+ \sum i_{mb} \sin(m\omega t + \varphi_{mb}) \\ i_c &= i_p \sin(\omega t + \varphi_p + 120) + i_n \sin(\omega t + \varphi_n - 120) \\ &+ \sum i_{mc} \sin(m\omega t + \varphi_{mc}) \end{aligned} \quad (1)$$

We can write this equation in matrix form as (2):

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = \left[i_{pos}\right] + \left[i_{neg}\right] + \left[i_h\right] \quad (2)$$

That $\left[i_h\right]$, $\left[i_{pos}\right]$ and $\left[i_{neg}\right]$ are vector of harmonics, positive and negative currents.

i_d and i_q are calculated by (3)

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix} = [T] \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} \quad (3)$$

[T] is transform matrix, if we choose voltage of phase a as reference, [T] will be as (4)

$$[T] = \frac{2}{3} \begin{bmatrix} \sin\omega t & \sin(\omega t - 120) & \sin(\omega t + 120) \\ \cos\omega t & \cos(\omega t - 120) & \cos(\omega t + 120) \end{bmatrix} \quad (4)$$

Same as a, b, c phase currents we can divide d, q currents to different components. We can show that components of d, q currents that are produced by positive sequence current are:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix}_{pos} = [T]\left[i_{pos}\right] = i_p \begin{bmatrix} \cos\varphi_p \\ \sin\varphi_p \end{bmatrix} \quad (5)$$

Equation 5 shows that positive sequence component of load current make a constant value of i_d and i_q. This component of i_d is equal to active component of positive sequence current of the load, in same way we can see that positive sequence component of the current i_q has a constant value equal to reactive component of positive sequence current of the load.

Components of d, q currents that are made by negative sequence current of the load current are:

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix}_{neg} = [T]\left[i_{neg}\right] = i_n \begin{bmatrix} \cos(2\omega t + \varphi_n) \\ \sin(2\omega t + \varphi_n) \end{bmatrix} \quad (6)$$

Equation 6 shows that negative sequence component of the load current produce sinusoidal wave current in d, q system, magnitude of these currents are equal to magnitude of negative sequence component of the load current. Frequency of these waves is two times of frequency of the system. Negative sequence components of the currents i_d and i_q have 90° phase respect each other.

Components of d, q currents those are made by harmonics of load current are calculated by (7).

Equation 7 shows that harmonics order m of the phase currents of the system produce sinusoidal wave with frequency m+1 and m-1 times of supply system frequency in d, q system. If current has only odd harmonics, frequency of the i_d and i_q components will be even.

$$\begin{bmatrix} i_d \\ i_q \end{bmatrix}_h = \frac{1}{3}\sum \begin{bmatrix} i_{ma}\{\cos[(m+1)\omega t+\varphi_{ma}]+\cos[(m-1)\omega t+\varphi_{ma}]\} \\ +i_{mb}\{\cos[(m+1)\omega t+\varphi'_{mb}]+\cos[(m-1)\omega t+\varphi'_{mb}]\} \\ +i_{mc}\{\cos[(m+1)\omega t+\varphi'_{mc}]+\cos[(m-1)\omega t+\varphi'_{mc}]\} \\ i_{ma}\{\sin[(m+1)\omega t+\varphi_{ma}]+\sin[(m-1)\omega t+\varphi_{ma}]\} \\ +i_{mb}\{\sin[(m+1)\omega t+\varphi'_{mb}]+\sin[(m-1)\omega t+\varphi'_{mb}]\} \\ +i_{mc}\{\sin[(m+1)\omega t+\varphi'_{mc}]+\sin[(m-1)\omega t+\varphi'_{mc}]\} \end{bmatrix}$$

$$\varphi'_{mb} = \varphi_{mb} - 120 \qquad \varphi'_{mc} = \varphi_{mc} + 120 \qquad (7)$$

Equations 5, 6 and 7 show that:

1- Average value of the i_d ($i_d|_{av}$) current in half period of system current show the active components of the current.

2- Average value of the i_q ($i_q|_{av}$) current in half period of system current show the reactive components of the current.

3- Time variable components of i_d (i_d - $i_d|_{av}$) and i_q (i_q - $i_q|_{av}$) show the effect of harmonics and negative sequence currents.

The relation between components of i_d and i_q and components of and i_a, i_b and i_c is as shown in table 1

Same as (3) we can write

$$\begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} = [T]^{-1}\begin{bmatrix} i_d \\ i_q \end{bmatrix} \qquad (8)$$

In this equation $[T]^{-1}$ is

$$[T]^{-1} = \begin{bmatrix} \cos\omega t & \sin\omega t \\ \cos(\omega t-120) & \sin(\omega t-120) \\ \cos(\omega t+120) & \sin(\omega t+120) \end{bmatrix} \qquad (9)$$

So if i_{ac} , i_{bc} and i_{cc} show the phase currents of the converter and i_{dc} and i_{qc} show currents of converter in "d-q" system, we have

$$\begin{bmatrix} i_{ac} \\ i_{bc} \\ i_{cc} \end{bmatrix} = [T]^{-1}\begin{bmatrix} i_{dc} \\ i_{qc} \end{bmatrix} \qquad (10)$$

Respect (10) if we want to calculate phase currents of an active filter it will be enough calculate currents of the active filter in the "d-q" system.

Components of i_d and i_q	Components of i_a, i_b and i_c
DC component	Active and Reactive currents
Second harmonic	Negative sequence current
Higher harmonics	Harmonics of Current

Table 1- relation between components of i_d and i_q and i_a, i_b , i_c

Table 2 shows different chose of i_{dc} and i_{qc} for different object of compensation

3.POWER CIRCUIT

In this research an active filter is add to the system to inject harmonics, reactive and negative sequence components of load current so supply system only fed active component of current. Voltage source PWM converter same as figure 1 usually is used as an active filter. Insulated-gate bipolar transistor (IGBT) or gate-turn-off thyristor (GTO) can be used as switches in figure 1.

Because of heavy load and existence of high order harmonics in railway system, active filter is needed components with high power and high switching frequency. GTO has low switching frequency and IGBT has low power, to overcome this problem parallel active filters is used to increase power and switching frequency of active filter. m parallel active filter with power p and switching frequency of f_s and 360°/m difference is phase of triangular switching wave has same effect with an active filter with power mp and switching frequency of mf_s. In this research four parallel active filters are used to increase power of active filter. Because parallel active filters have triangular wave with same magnitude and 90° delay in phase, the effect of switching frequency is four times of switching frequency of each active filter. Series reactance is used to decrease effect of harmonics of the voltage at converter side, the larger inductance has the better result but higher DC voltage on capacitor and higher cost, X_d=25% is chosen in this paper.

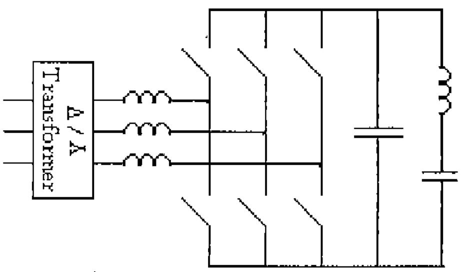


figure1-Voltage source PWM

Object of compensation	i_{dc}	i_{qc}
reactive power	0	i_{qpos}
Harmonics and negative sequence current	$i_{dneg}+i_{dh}$	$i_{qneg}+i_{qh}$
Harmonics, negative sequence and reactive current	$i_{dneg}+i_{dh}$	$i_{qneg}+i_{qh}+i_{qpos}$

Table 2- i_{dc} and i_{qc} for different object of compensation

A 9mF capacitor is installed as reactive element of the converter to decrease oscillation of the voltage at DC side, capacity of capacitor has reverse effect on the magnitude of voltage oscillation. Voltage of capacitor must be chosen carefully because internal voltage of converter that control current of converter is proportional to voltage of capacitor, in addition cost of all elements those are connected to DC side are proportional to voltage of DC side.

A second harmonic filter is used at DC side to omit second harmonic of the voltage.

A three-phase transformer is used to decrease voltage of supply system (usually 27.5 kV) to practical value for power electronics elements. In this paper a three-phase star/delta transformer is used to decrease turn ratio of windings (N_1/ N_2) and effect of unbalanced current on active flitter. Because of different phase angle between currents of primary and secondary side of star/delta transformers control of the active filter is more difficult. When four parallel PWM unit is used as an active filter we can use one transformer for each PWM unit in this case we can use series connection in primary side to decrease turn ratio or parallel connection to increase reliability of active filter. We can use a common transformer for all of the active filters to decrease the cost.

4.CONTROL SYSTEM

For control system of active filter figure 1, compensating of the harmonics, reactive current and negative phase sequence current is chosen as object and currents of active filter is chosen as shown in table 2. Control system of this circuit has two parts .

1-reference calculator

2-switching frequency control (active filter control)

At first part two line voltage and two line current of the load enter as input data. Voltages and currents of the load phases are calculated in this part, then currents of the load at d, q system are calculated by (3). Table 2 show that currents of the active filter in d, q system must be:

$$\begin{bmatrix} i_{dc} \\ i_{qc} \end{bmatrix} = \begin{bmatrix} i_{dneg} + i_{dh} \\ i_{qneg} + i_{qh} + i_{qpos} \end{bmatrix} = \begin{bmatrix} i_d - i_{dpos} \\ i_q \end{bmatrix} \tag{11}$$

Equation 5 shows that i_{dpos} has a constant value that can be calculate by integral of the i_d in half period. Active filter must not absorb or produce active power at normal condition in some researches current sensors are considered for control of active power of the active filter.

Active power of an active filter can change the voltage of capacitor so if we keep voltage capacitor constant the active power of active filter will be zero [4] so we needn't use additional current sensors. In cases that voltage of capacitor is not equal to reference value a balance active current must be add to phases currents of active filter to compensate voltage of capacitor, this current can be calculated by (12) in dq system

$$i_{dcap} = \frac{\frac{\sqrt{2}}{2} c(v_{ref}^2 - v_{cap}^2)}{\sqrt{3}.v} \tag{12}$$

In (12) v, v_{ref}, v_{cap} and c respectively are source voltage, reference voltage, capacitor voltage and capacity of capacitor. For case that deviation from reference voltage is small (12) can be simplified. Equation 13 shows simplified form of (12).

$$i_{dcap} = \frac{c v_{ref} (v_{ref} - v_{cap})}{\sqrt{6}.v} \tag{13}$$

So (11) is replaced by (14)

$$\begin{bmatrix} i_{dc} \\ i_{qc} \end{bmatrix} = \begin{bmatrix} i_{dneg} + i_{dh} \\ i_{qneg} + i_{qh} + i_{qpos} \end{bmatrix} = \begin{bmatrix} i_d - i_{pos} - i_{dcap} \\ i_q \end{bmatrix} \tag{14}$$

Phase currents of the active filter are calculated by (10) at next step. Finally required value of the internal phase voltages of the active filter are calculate by:

$$\begin{bmatrix} v_{ac} \\ v_{bc} \\ v_{cc} \end{bmatrix} = \begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} + (r + L\frac{d}{dt}) \begin{bmatrix} i_{ac} \\ i_{bc} \\ i_{cc} \end{bmatrix} \tag{15}$$

That v_{ac}, v_{bc} and v_{cc} are internal phase voltages of active filter, v_a, v_b and v_c are phase voltages of supply system, r and L are the parameter of series inductance.

Switching strategy of active filter is designed at second part of control system. Triangular switching strategy is chosen for this part because algorithm of this method is simple and it needn't any additional calculation and extra memory for save any information so it will be very fast.

A triangular wave with magnitude one can control switching of the switches, frequency of switching is equal to frequency of this wave so this method have a constant switching frequency. At first step modulation waves are calculated by (16). [5]

$$\begin{bmatrix} mod_a \\ mod_b \\ mod_c \end{bmatrix} = \frac{2}{v_{cap}} \begin{bmatrix} v_{ac} \\ v_{bc} \\ v_{cc} \end{bmatrix} \tag{16}$$

At second step, modulation waves compare with triangular wave. Figure 2 shows the block diagram of the control system.

5.RESULT OF SIMULATION

This section present simulation result of circuit that was shown in figure 1, control strategy is same as is shown in figure 2. All of simulation was done by Saber software. At first step a single-phase reactive load 27.5 kV, 200kVA, Cosφ=0.8 lag with 33% third and 20% fifth was compensated by active filter. The second load was a 200kw single-phase rectified load. Voltage of DC side will be high because negative sequence, harmonics and reactive current are compensated at same time. DC voltage is chosen equal to 3900 V, because at DC voltage less than 3900V over modulation happen and DC voltage more than 3900V increase cost of capacitor and magnitude of internal voltage harmonics. Frequency of triangular wave is 1950Hz. Figures 3 and 4 show the results of simulation for first and second loads. Figures 3-a and 4-a show voltage of DC side. These figures indicate that control system can keep voltage near the reference value. These voltages have small value of second and high order harmonics those are made by harmonics and negative phase sequence of AC side currents. We can decrease the magnitude of these harmonics by passive filter if we need. Figures 3-b and 4-b show currents of the three phases of supply system. These figures show that currents of the system approximately are balance and magnitude of lower harmonics of currents are decreased considerably, Active filter compensate negative sequence current of the supply system up to 0.8%. Figures 3-c and 4-c show harmonics spectrum of source currents. These figures show that the magnitude of low order (third, fifth and seventh) harmonics have small value (less than 2.5%), but currents has large magnitude harmonics at frequency near to switching frequency (at 850,1050 Hz, 8.7%) and two times of switching frequency (at 1850, 1950Hz, 5.8%). These figures show that low order harmonics are compensated considerably. Magnitude of harmonics at frequency near to switching frequency and its multiplier are less than 9%. So it seems this circuit successfully can compensate harmonics, reactive current and unbalancy of the load. High order harmonics must be compensated by passive filter if it is needed.

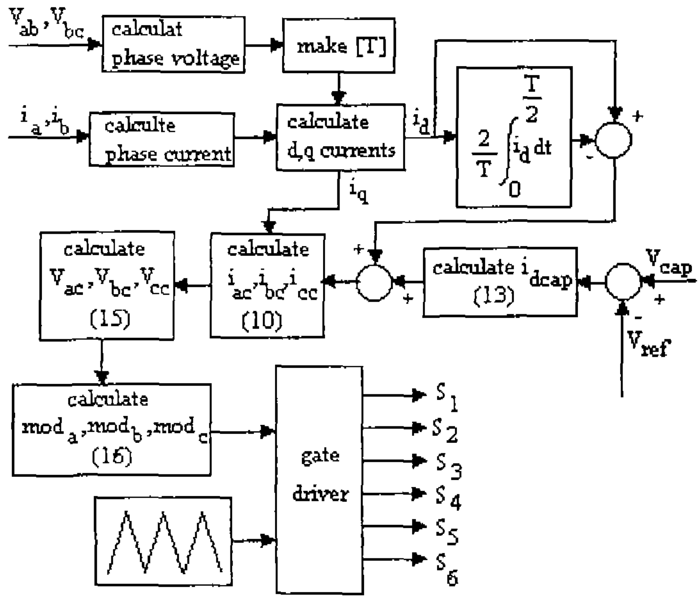
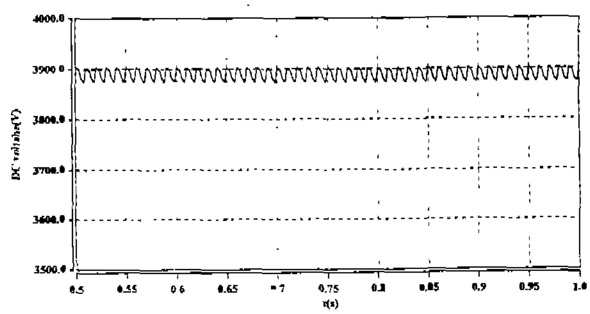
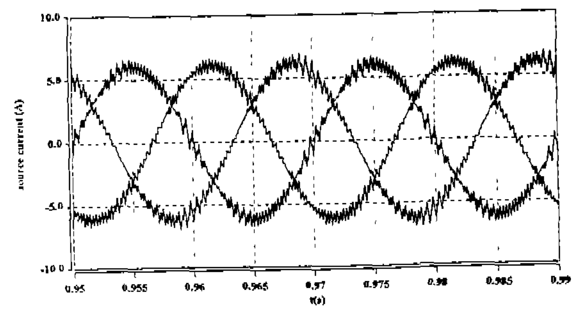


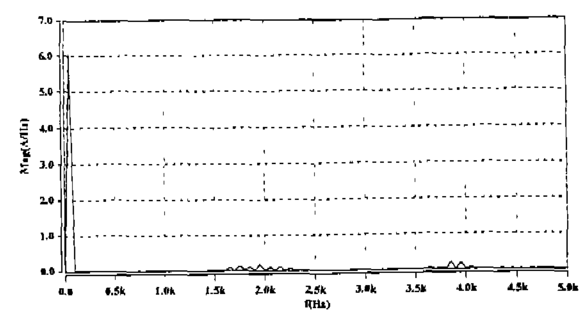
Figure 2-block diagram of the control system



a) Voltage of DC side

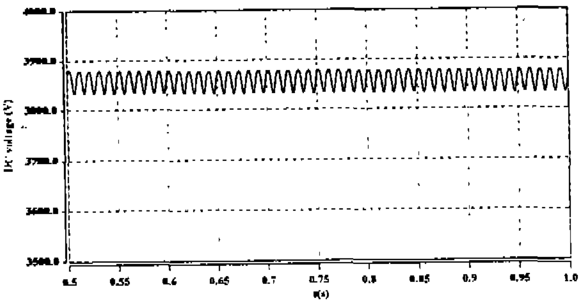


b) Source currents

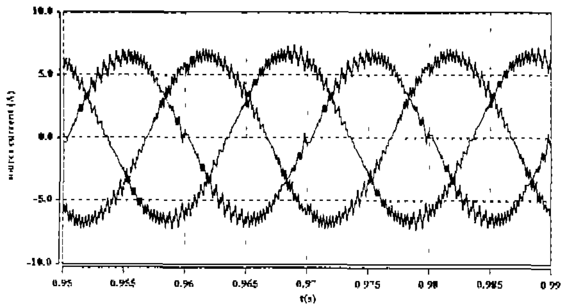


c) Harmonics spectrum

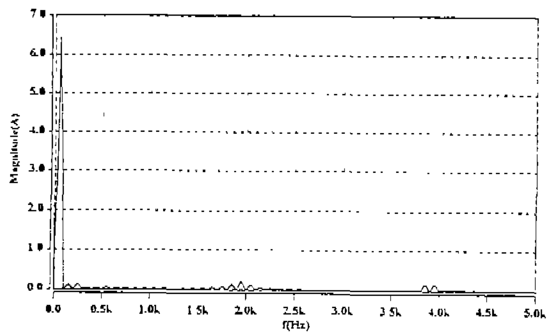
Figure 3- Result of load 1



a) Voltage of DC side



b) Source currents



c) Harmonics spectrum

Figure 4- Result of load 2

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