Mitigation of Voltage Unbalance in Traction System

B.R.Lakshmikantha, Dr Murugesh Mudaliar, Dr K.Balaraman, Dr R.Nagaraja

Abstract : **Electric traction has become mainstay in the transportation sector due to its lack of pollution, higher performance, lower maintenance cost and lower energy cost. However, the electric traction system introduces unbalance in the system which affects the critical loads. In this paper, the cause of unbalance due to traction system is investigated along with its effects on critical load. An approach for balancing the power supply is given by the use of FACTs technology and implementation aspects are discussed in this paper.**

***Keywords*: FACTS, Static Var Compensators, Stability, Traction system.**

I. INTRODUCTION

An electric locomotive is a locomotive powered by electricity from an external source. Sources include overhead lines, third rail or an on-board storage device such as a battery or a flywheel energy storage system. Electric locomotives can accelerate extremely quickly, limited only by what the infrastructure can withstand; making them ideal for commuter service with its many stops. Electric locomotives can run in their most efficient mode, where as turbine-driven locomotives, are inefficient at low speeds. Additional efficiencies can be gained from regenerative braking, which allows much of the kinetic energy of the train to be recovered and used to power other locomotives on the line.

Electric traction is generally considered the most economical and efficient means of operating a railroad, provided that cheap electricity is available and that the traffic density justifies the heavy capital cost. Being simply power-converting, rather than power-generating devices, electric locomotives have several advantages. They can draw on the resources of the central power plant to develop power greatly in excess of their nominal ratings to start a heavy train or to surmount a steep grade at high speed. A typical modern electric locomotive rated at 6,000 horsepower has been observed to develop as much as 10,000 horsepower for a short period under these conditions Most of the traction loads are single phase loads.

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B.R.Lakshmikantha is a faculty member in Bangalore Institute of Technology and research scholar from B.M.S.College of Engineering, affiliated to VTU, e-mail: lkantha@indiatimes.com .
Dr Murugesh Mudaliar is professor of P.G.Studies, B.M.S.College of Engineering.
Dr Balaraman is C.G.M at Power Research & Development Consultants, Bangalore, e-mail: balaraman@prdcinfotech.com.
Dr R.Nagaraja is M.D of Power Research & Development Consultants, Bangalore, e-mail: nagaraja@prdcinfotech.com.

The traction transformer is supplied from two phases, normally at 220 kV or 110/132 kV voltage levels. In order to balance the load, traction substations are fed from RY phase, YB phase and BR phases at equal intervals. However, if the trains or locos are running only in a particular section, large unbalance is seen in the 3 phase system. The unbalance voltage is appreciably large and affects the other connected loads, if the AC system is reasonably weak.Tsai-Hsiang, et.al [1] has introduced a systematic approach to the evaluation of the overall impact of the electric traction demands of a high-speed railroad (HSR) in power system. The large unbalanced traction loads may cause system voltage and current unbalances and, therefore, overheat rotating machines, increase system losses, interfere with neighboring communication systems, and cause protection relays and measuring instruments to malfunction. Some of these problems may significantly affect the operation of the power system and other equipment connected to it. Hence, the proposed approach is oriented toward applications in system operation analysis rather than planning analysis. Dr Johan Driesen and Dr Thierry Van [2] have explained the cause for imbalance in an electric system. The balance of the equivalent load at the central transformer fluctuates because of the statistical spread of the duty cycles of the different individual loads. Abnormal system conditions also cause phase unbalance. Phase-to-ground, phase-to-phase and open-conductor faults are typical examples. These faults cause voltage dips in one or more of the phases involved and may even indirectly cause over voltages on the other phases. The system behavior is then unbalanced by definition, but such phenomena are usually classified under voltage disturbances. T. J. E. Miller [3] has clearly explained the phase compensation for balancing the unbalanced system.

II.THREE-PHASE VOLTAGE IMBALANCE

A three-phase power system is called balanced or symmetrical if the three-phase voltages and currents have the same amplitude and are phase shifted by 120° with respect to each other. If either or both of these conditions are not met, the system is called unbalanced or asymmetrical.

The system operator tries to provide a balanced system voltage at the point of common coupling between the distribution grid and the customer's internal network. Under normal conditions, these voltages are determined by the:

- Terminal voltages of the generators
- Impedance of electricity system
- Currents drawn by the loads throughout the transmission and distribution grid.

The system voltages at a generation site are generally highly symmetrical due to the construction and operation of synchronous generators used in large centralised power plants. Therefore, the central generation does not in general contribute to unbalance. Even with induction (asynchronous) generators, as used for instance in some types of wind turbines, a balanced three-phase set of voltages is obtained. However, where small-scale distributed or embedded generation, installed at the customer's site, has become more popular and taken up a significant share of the electricity production, the situation is different. Many of these relatively small units, such as photovoltaic installations, are connected to the grid at LV by means of single-phase power electronic inverter units. The connection point has a relatively high impedance (the short-circuit power is relatively low), leading to a potentially larger unbalance of the voltage than is the case for connections at higher voltage level.

The impedance of electricity system components is not exactly the same for each phase. The geometrical configuration of overhead lines, asymmetric with respect to the ground for instance, causes a difference in the electrical parameters of the line. Generally, these differences are very small and their effect can be neglected when sufficient precautions, such as the transposition of lines, are taken.

In most practical cases, the asymmetry of the loads is the main cause of unbalance. At high and medium voltage level, the loads are usually three-phase and balanced, although large single- or dual-phase loads can be connected, such as AC rail traction (high-speed railways) or induction furnaces.

Wherever possible, efforts are made to distribute the single-phase loads uniformly over three phases. From a statistical point of view, however, distributing single-phase loads uniformly over the three phases only ensures that the expected values of the loads in each phase will be approximately equal. But it is unlikely that at a given instant, three-phase loads will be balanced because they vary in a random manner. In other words, even if the average loads in the three phases are kept the same, the instantaneous power demands in the three phases differ from each other, leading to imbalanced voltages at the point of common coupling. The degree of imbalance of a three-phase voltage is often measured based on the ratio of its negative- to positive-sequence component. This ratio is termed the unbalance factor (UBF) [4].

Unbalance is a serious power quality problem, mainly affecting low-voltage distribution systems, overheating of rotating machines, increase in system losses, interfere with neighboring communication systems, and cause protection relays and measuring instruments to malfunction. Some of these problems may significantly affect the operation of the power system and other equipment connected to it.

III. PROBLEM DEFINITION

In order to analyze the problem of imbalance voltage of traction system, a practical 21 bus AC system, part of a larger system is considered as shown in figure 1. A "Test-centre" is about 43 KMs from Bus-19. Power supply to the "Test-centre" is obtained through a 33 kV over head line from 132/33 kV substation. The 33 kV line is about 43 KMs and the conductor configuration is triangular type with Dog conductor. Bus-19, 132 kV substation receives the power supply from Bus-3, 220/132 kV station. In between Bus-3 and Bus-19, there are 4 traction substations getting supply from the Bus 3-18, 132 kV double circuit line. The Bus-3, 220 kV substation is supplied from Bus-1, 220 kV station through 223 km, 220 kV single circuit line. Bus-3, 220/132 kV station also supplies power to Bus-10,132 kV substation.
At Bus-21, substation, the power is stepped down to 11 kV through 3 no. 33/11 kV power transformers. The power is further stepped down to 433 V at different load center feeding substations using 11kV/433V distribution transformers. In the Bus 10-18 traction section, peak of about 24 up/down trains run per day. The average figure per day is 20 up/down trains. The peak current drawn from the up-train is about 500 A at 22 kV. This works to about 11 MW. The power factor is about 0.9 because of 1 x 3360 kVAR capacitor bank being installed at traction substation. It is found at the "Test-centre" connected from Bus 21 the drive loads are tripping frequently due to "supply phase" fault (as indicated in the display panel).

It is required to analyze the power supply system in detail and to arrive at reliable system correction devices to be incorporated at the "Test-centre" to achieve stable power supply. The single line diagram of the electrical network is shown in Figure 1. Table 1 gives the bus details considered for the study.

IV. MEASUREMENT DETAILS

In order to determine the voltage profile and system unbalance, meter readings were taken at typical locations. It is found that the voltage at individual phases was varying drastically at times. The voltages recorded at any time instant were very much different in the individual phases. With grid supply, tripping of DC drive system was also observed. The fault indicated in the drive is "supply phase". As per the drive manual the cause for the same is "Intermediate circuit DC voltage is oscillating".

This could be caused by a missing mains phase, a blown fuse or a rectifier bridge internal fault. A trip occurs when the DC voltage ripple is 13 % of the DC voltage". The random readings of the line voltages and the line currents at the "Test-Centre" at Bus-21 are recorded in table 1.

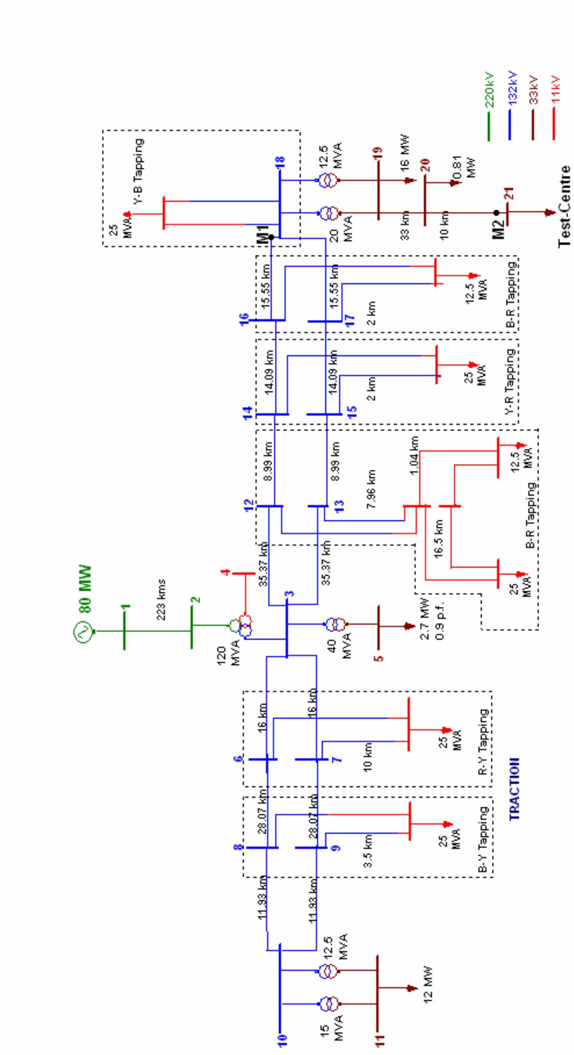


Figure 1: AC System with traction loads

It is seen that the voltages and currents are unbalanced and there would be frequent tripping. In order to determine the cause for tripping of the drives at the “Test-Centre”, the following tests were conducted to check the healthiness.

As a first check, the grid supply was disconnected and the plant was run with DG system. It was found that the drive systems worked normally and no tripping was observed.

As a second check, the healthiness of the 33/11 kV transformer at the test centre at Bus 21 was tested. The transformer was disconnected from the grid and the 11 kV generation from DG system was stepped up to 33 kV through one 33/11 kV transformer and further stepped down to 11 kV and power was distributed It was again found that the drive systems worked normally and no tripping was observed.

It is clearly seen that the problem lies with the supply system unbalance.

Table1: Supply Through Grid 33/11/0.433 kV

Phase	R-Y	Y-B	B-R	R	Y	B
Voltage in Volts	403	408	425			
Current in Amps				92	59	76
Through 11 kV DG Supply Directly - 11kV/0.433 kV						
Voltage in Volts	440	440	440			
Current in Amps				84	86	85
Through DG supply & 33 kV grid - 11/33/11/0.433 kV						
Voltage in Volts	449	450	450			
Current in Amps				81.5	82.5	80

The field measurements M1 was undertaken at line near bus 18 (between bus 16 & bus 18) at 132 kV voltage level, the readings of the phase voltages were taken for about one hour forty minutes with an interval of 30 seconds. The readings were tabulated and the graph was plotted. Figure 2 show the plot of phase voltage with respect to time for transmission lines at bus 18.

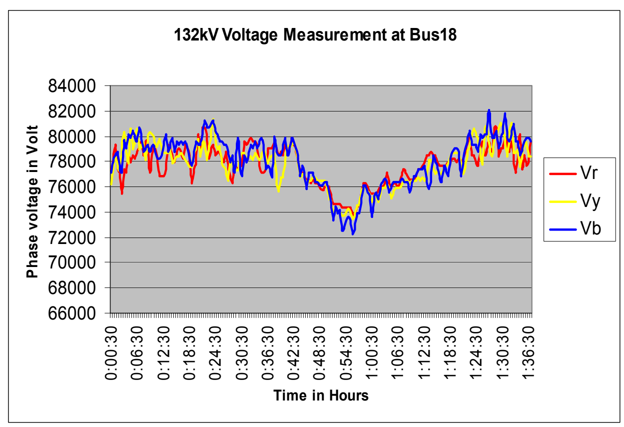


Figure2: Plot of Phase Voltages at Bus 18

From figure 2, it is seen that at 00:03:00 hours the voltage in R, Y and B phases are 75438 volts, 79198 volts and 77153 volts with an unbalance of 2.36% in R-phase, 2.5% in Y-phase to average and 0.139% in B-phase to average and at 00:39:00 hours the voltage unbalance is 1.17% in R-phase, 2.432% in Y-phase and 1.26% in B-phase to average.

V. THREE PHASE LOAD FLOW STUDIES

Three phase load flow studies were conducted for the given system with the cases, viz, no traction load, equal traction load, traction load connected in either R-Y, Y-B or B-R, traction load connected in combination of R-Y&Y-B, Y-B&B-R or B-R&R-Y, no traction load with 15% unbalance and with traction load with 15% unbalance voltages. The individual phase voltages, the positive and negative phase sequence voltages at Bus 21 (near the "Test-Centre") are tabulated in table 2.

From the results it is observed that there has been a substantial unbalance in the voltage (negative sequence voltage), where the drive loads are connected.

Table 2: Three Phase Load Flow Study results at Bus-21, 33 KV for different load conditions

Case No	Description	R-phase voltage in pu	Y-phase voltage in pu	B-phase voltage in pu	Positive sequence voltage in pu	Negative sequence voltage in pu
1	No Traction	0.927	0.926	0.927	0.927	0.001
2	Equal T.L*	0.886	0.886	0.879	0.884	0.005
3	T.L in R-Y	0.912	0.821	0.920	0.883	0.062
4	T.L in Y-B	0.919	0.909	0.812	0.878	0.066
5	T.L in B-R	0.808	0.919	0.906	0.876	0.068
6	R-Y & Y-B	0.911	0.817	0.919	0.881	0.064
7	Y-B & B-R	0.866	0.913	0.867	0.881	0.032
8	B-R & R-Y	0.875	0.872	0.915	0.887	0.028
9	N.T.L & 15% U.B	0.922	0.950	0.926	0.932	0.018
10	T.L & 15% U.B	0.880	0.912	0.878	0.890	0.022
11	Compensation + T.L in B-R	0.920	0.928	0.928	0.925	0.006

T L* = Traction Load

Table3: Compensation at Bus -21 33KV

Sl.No	Phase	Compensation
1	R-Y	2 MVAR Capacitive
2	Y-B	0.65 MVAR Inductive
3	B-R	0.7 MVAR Capacitive

VI. ANALYSIS and RESULTS

In order to alleviate the unbalance study was conducted with static compensation at Bus-21, with case 5 condition.

It was also seen from the simulation studies conducted that the unbalance exists with different traction loading conditions. It is proved that with dynamic compensation (based on the typical case study) the supply voltage unbalance at the "Test-Centre" could be rectified.

The compensation provided is given in Table 3. From the results it is seen that the voltage unbalance at the Bus-21, and also in the down stream is completely nullified.

With the static load flow results the value of ±7.5 MVAR Static Var Compensator (SVC) at Bus-21, 33 kV is determined. The ±7.5 MVAR SVC will consist of 7.5 MVAR filter banks tuned as 5^{th} harmonic, 7^{th} harmonic and a high pass filter.

At fundamental frequency, these capacitor banks will provide 7.5 MVAR at 33 kV. The reactor is of 15 MVAR controlled through the thyristor bridge-firing angle. It is recommended to install 5 MVAR, 3^{rd} harmonic filter at Bus-19, 132 kV substation. This filter will provide 5 MVAR compensation at fundamental frequency and filter the 3^{rd} harmonic current in the system.

The SVC recommended will have individual phase compensation, so that voltage in each phase can be corrected and adjusted to nominal value. As it is economical, TCR part of the SVC will use suitable step down transformer to match the thyristor voltage rating [5].

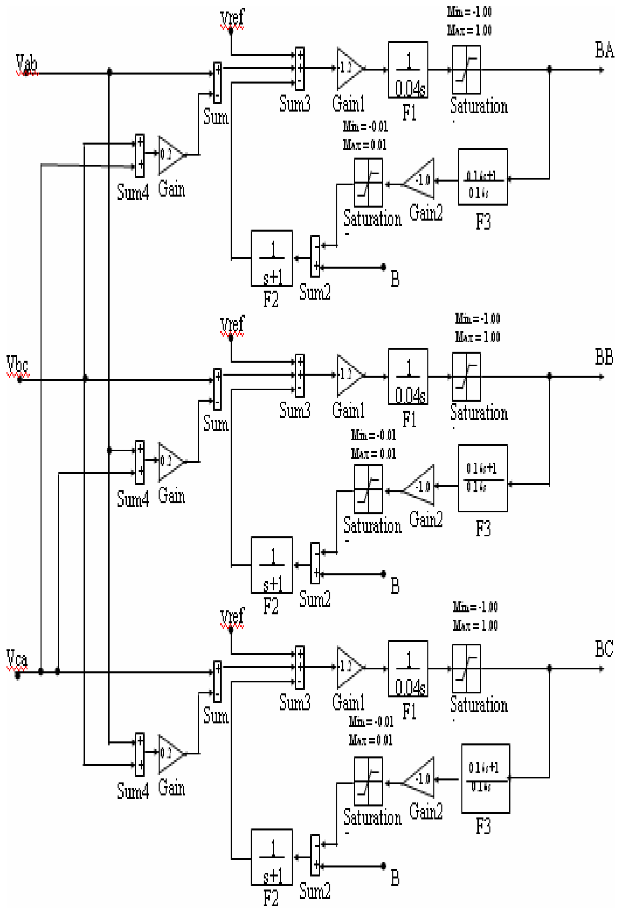
VII. CONTROL PARAMETERS OF SVC

The primary purpose of the control of the SVC is to control system voltage. This is accomplished by having the SVC supply leading or lagging reactive power in response to measured system variables or operator inputs. The control shall be of Phase voltage control, based on Individual phase voltages

SVC control characteristics

a) The operating characteristic of the SVC control is illustrated in figure 3.

- The reference voltage (V_{ref}) and minimum/maximum values (V_{ref} min and V_{ref} max) with complete adjustment capability of the voltage reference set point (which equals zero SVC output) at any value within the specified range



BA: Compensation in phase A
BB: Compensation in phase B
BC: Compensation in phase C
Figure 4: Block diagram of individual phase compensation SVC

- The slope (SL) of the voltage control characteristic, including minimum and maximum values (SL) of the voltage control characteristic, including minimum and maximum values (SL min / SL max). The slope of the V/I characteristic should be continuously adjustable between 0.5% and 10%, based on total Mvar continuous operating range.
- Range of control
- Overall accuracy of the controlled voltage (±1%) and the linearity of the maximum slope with the control range (±10%)

b) The dynamic characteristic of the SVC control is the response (SVC current I) to a small step change (linear range of control) in the voltage reference value or in any input quantity “X” at defined system conditions.

VIII. COMPENSATION

An Individual phase compensated ± 7.5 MVAR Static Var Compensator as shown in figure 4 is considered at bus 21 to mitigate the problem of large unbalanced voltage seen in the system.

Signal BM is the mean value of susceptances B_{AB}, B_{BC} and B_{CA}. The saturation block in the forward path provides an upper and lower bound on the respective susceptances B_{AB}, B_{BC} and B_{CA}. These upper and lower limits are maximum and minimum values for susceptances in pu.
$B_{MIN} = -(Q_{MAX}/SN)$
$B_{MAX} = -(Q_{MIN}/SN)$
Where
Q_{MAX} is the max reactive power absorbed by SVC
Q_{MIN} is the min reactive power absorbed by SVC
SN - Rated power of SVC
In case of SVC with symmetrical V-I characteristics in inductive and capacitive mode, for example ± 7.5 MVAR, the rating SN = 7.5 MVAR.

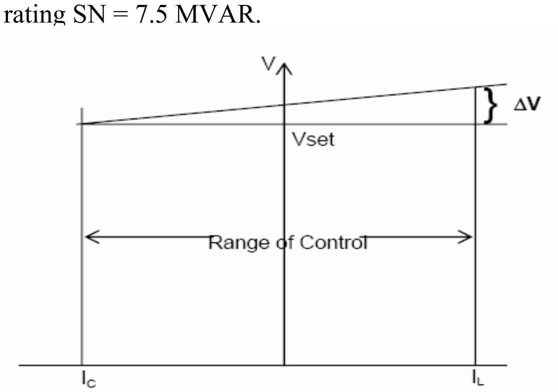


Figure3: V-I characteristics of SVC

The sign of Q_{MAX} and Q_{MIN} within parentheses is taken as positive when SVC is inductive and negative when SVC is capacitive.

The saturation block in the feed back loop provides upper and lower bounds on the difference signal (B-BM) where B is the susceptance B_{AB} or B_{BC} or B_{CA}. In the present study the maximum and minimum values are taken as ± 0.01 respectively.

Figures 5 to 8 show the SVC response when sudden unbalance load at traction substation is applied. From the figures, it is concluded that individual phase compensation SVC is best suited to correct the voltage unbalance seen in weak system with traction loads

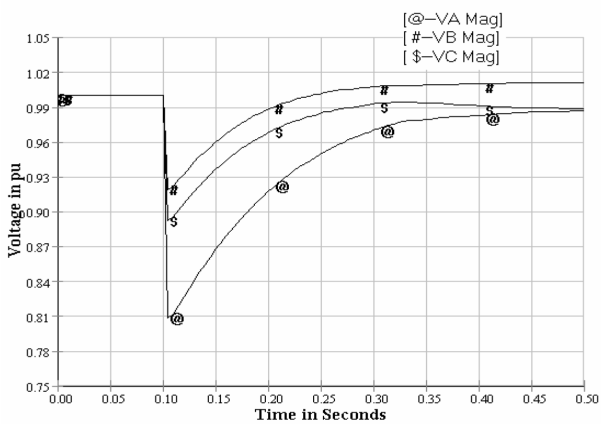


Figure 5: Phase voltage

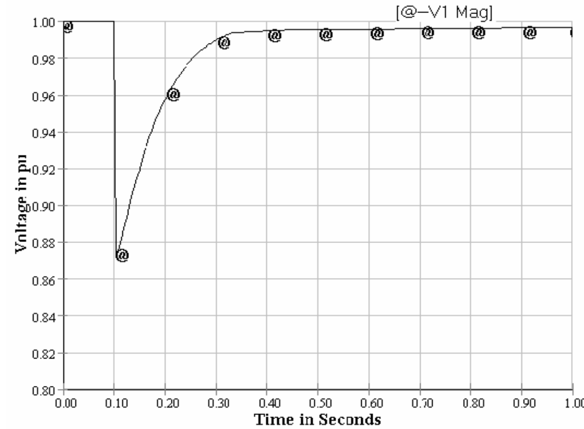


Fig 6: Positive sequence voltage

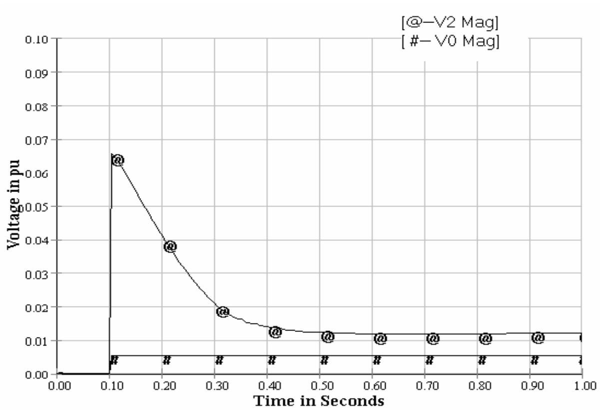


Figure 7: Negative and Zero sequence voltage

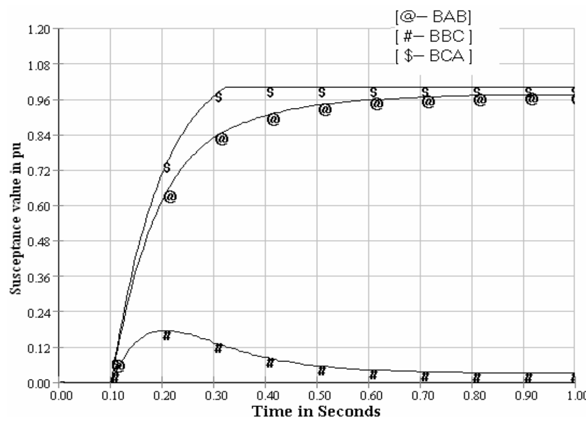


Figure 8: SVC output – suceptance value

IX. CONCLUSION

There is no substitute to electric locomotives for pollution free high speed transportation, however the large unbalanced traction loads may cause system voltage and current unbalances and, therefore, overheat rotating machines, increase system losses, interfere with neighboring communication systems, and cause protection relays and measuring instruments to malfunction. Some of these problems may significantly affect the operation of the power system and other equipment connected to it.

The system studies reveal that with the application of individual phase compensation SVC, it is possible to maintain the balanced voltage profile irrespective of the traction loading conditions.

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REFERANCES

1. Tsai-Hsiang Chen; Wen-Chih Yang; Yen-Feng Hsu "A systematic approach to evaluate the overall impact of the electric traction demands of a high-speed railroad on a power system**",** IEEE Transactions on Vehicular Technology, Volume 47, Issue 4, Nov 1998 Page(s):1378 – 1384.
2. Dr Johan Driesen, Dr Thierry Van Craenenbroeck, "Voltage Disturbances Introduction to Unbalance", Katholieke Universiteit, Leuven, May 2002.
3. T. J. E. Miller "Reactive Power Control in Electric Systems*", John Wiley & Sons*, 1982, USA.
4. Li Zhang, Yilu Liu Michael R. Ingram, Dale T. Bradshaw Steve Eckroad Mariesa L. CrowE, " EAF Voltage Flicker Mitigation By FACTS/ESS", IEEE Transactions 2004
5. Narain G. Hingorani and Laszlo Gyugi "Understanding FACTS Concepts and Technology of Flexible AC Transmission systems" IEEE publications 2000.