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Power Quality Control in DC Traction Systems using Static VAR Compensator and Harmonic filter

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***Abstract*- The distribution network of electric traction systems gets high impact of power quality issues during its operation. In this paper a DC electric traction system was modeled with different scenarios in order to generate the problems that its operation implicated. A compensation device, SVC, was designed and added to the distribution network to improve voltage and also a filter was installed to reduce wave distortion. Finally the possible events that can appear due to the original impact of single traction load is evaluated.**

***Index Terms*— Direct Current Electric Traction Systems, Flexible AC Transmission Systems (FACTS), Mechanically Switched Capacitor (MSC), Static Var Compensator (SVC), Thyristor Controlled Reactor (TCR), Thyristor Switched Capacitor (TSC), Voltage Regulation, Wave Distortion.**

I. INTRODUCTION

The demand of electric traction systems are continually grows and nearly reaches the limit of traction power supplies that were previously designed. This significantly affects unstable, unreliable, inefficient, ineffective and uneconomical operations. Thus existing electric railway systems need to be upgraded.

In DC traction systems, the harmonic generation is the main problem. This is due to the presence of the rectifier substations in the network [2]. One key variable is vehicle movement on the system, due to the fact that it is the one that generates the variability on the demand [3] .

The first part of this paper shows a DC electric traction MATLAB/ SIMULINK model with 3 rectifier substations, a7.5km transmission line and a 2 source feeding system of 25kV. The demand on each of the rectifier substations was variable to approach the model to the characteristics of the behavior of the original system. To study the system in different environments, three cases were designed to analyze it : one in which the load and the variability were high and its counterpart of low load and variation and finally the original effect of single traction load from one station to other is implemented. The system was modeled in the software MATLAB with the aim of evaluating the THD produced and voltage reduction due to reactive power due to the fact that MATLAB/SIMULINK has enough tools to analyze power quality problems.

In the second part of the paper, designing and implementation of A Static VAR Compensator (SVC) and a Single tuned Harmonic filter to the above system to correct the power quality problems generated and evaluate the flexibility of the compensation.

II. DC TRACTION SYSTEMS

In DC traction systems, trains are constantly moving along the tracks and varying their positions and loads from time to time.There are a number of traction electrifications with different voltage levels in DC systems around the world, such as the 600V, 650V, 750V, 1500V and 3000V.

In fig.1.[10] an AC power supply is transformed and rectified to provide the DC traction voltage, connected to the substation's positive and negative busbars. Track feeders provide a feeder connected to the third rail or catenary through track feeder circuit breakers. The circuit breaker at each end of a faulted section must operate to isolate the fault. Each substation feeds from a common DC busbar through DC circuit breaker in both directions.

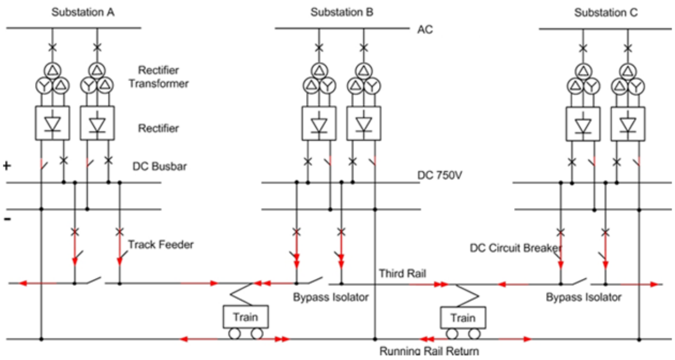

Fig.1. Typical DC railway system

III. DC TRACTION SYSTEMS IN INDIA

In India Traction voltages used are 1.5kV DC and 25kV AC for mainline trains. Calcutta had an overhead 3kV DC system until the '60s. The 1.5kV DC overhead system (negative earth, positive catenary) is used around Bombay (This includes Mumbai CST - Kalyan, Kalyan - Pune, Kalyan - Igatpuri, Mumbai CST - Belapur - Panvel, and Chuchgate - Virar). The Madras suburban routes (Madras-Tambaram in the '60s, extended later to Villupuram) used to be 1.5kV DC until about 1967, when it was converted to 25kV AC (all overhead catenary supply).

The Calcutta Metro uses 750V DC traction with a third-rail mechanism for delivering the electricity to the EMUs. The Calcutta trains use 550V DC with an overhead catenary system with underground return conductors. The catenary is at a negative potential. The Delhi Metro uses 25kV AC overhead traction with a catenary system on the ground-level and elevated routes, and uses a rather unusual 'rigid catenary' or overhead power rail in the underground tunnel sections

IV. ELECTRIC LOCOMOTIVES

DC motor is an ideal choice for traction purposes due to its wide operating speed range. In DC series machines the ratio of armature to field mmf is better regulated against supply variation than for alternative configurations[11]. So it had widespread application in traction drives. A basic configuration (as in Fig. 2) corresponding to electric locomotives (with rectifiers and DC motors) fed from AC the contact line is considered to be a basic structure. The electric locomotives (with DC motors) are fed from AC contact line both autotransformer (AT) and main traction transformer (TP) is unique, regardless of the number of rectifiers defined. For limiting the load current corrugations of the dc motor are used, in series (with saturated iron core).

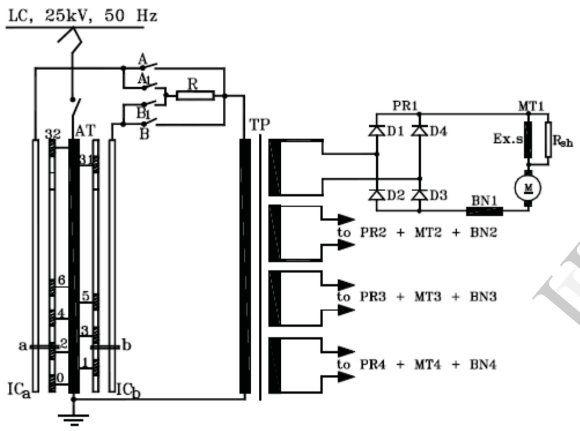

Fig.2. Electric locomotives with rectifiers and DC motors

V. DC FEEDING SYSTEM

The system that it is going to be analyzed and compensated is a direct current electric traction system. The Project model of DC feeding scheme is shown in fig.3. From the high voltage grid, two substations are connected at each end of the transmission line; each one of them is connected to rectifier substations to provide power to the catenary at the desired DC level. Power is fed to the vehicle through a conductor cable connected to the catenary system. The catenary system will feed the vehicle at 750V.

VI. POWER QUALITY PROBLEMS

Differet power quality phenomena that can appear are: voltage fluctuations, voltage and current distortion, voltage sags, voltage transient, and voltage and current unbalances [4]. All of the power quality phenomena appears due to the presence of non linear loads which is the case in the traction system in study because the power demand of the rectifier substations depends on the vehicle traffic at the time.

The key problem to the network is caused by the rectifier substation, which is an additional component in the DC electric traction system. It produces waveform distortions and consequent harmonic generation. The IEEE 519-1992 states that these types of rectifiers generate odd harmonics except for multiples of three, either it is a 6 or 12 pulse rectifier that is being used [5]. In this Direct current electric traction systems three rectifier substations are supposed, in larger systems there can be more rectifiers.

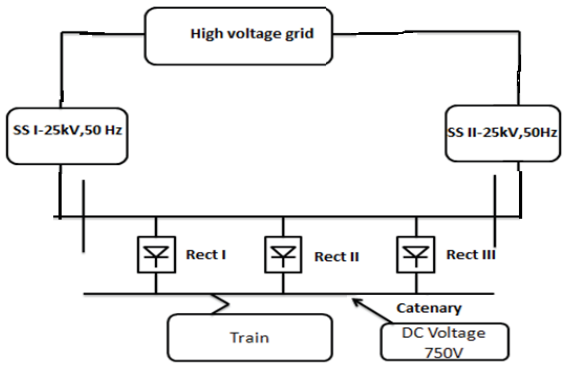

Fig. 3. DC Electric traction feeding scheme

It is important to point out the fact that in a two source system harmonics will flow equally to each one of them and propagate the problem all over the network.

VII. MODELING AND SIMULATION OF THE SYSTEM ON MATLAB

The main feeding system modeled was with two 25 kV sources connected to a 7.5km line. The transmission line was divided into three stages of 2.5km each.

In each one of the stages a rectifier substation was installed. Each one of them had a transformer with a 25/0.6kV relation due to the fact that the 6 pulse rectifier gives an output in DC that is around 1.35 times the line to line voltage that is fed [5]. Through this factor the feeding voltage was calculated in order to achieve the 750V desired.

Three breakers are programmed to switch on or off to simulate the load variability that the system have. One breaker enabled the rectifier substation to the whole system, and the other two added or subtracted load to it in order to change its particular demand when connected to the network.

Study Cases

To analyze the system, and the power quality problems generated three scenarios were created; one with low load and variability second is high variability of the load with more of a stepwise variation and the last is implementing the effect of a single traction load. Through these examples a demand on peak hours, and the other one with a demand on what is known as “valley hours” which is the time lapse of less demand can be created. Figure 4 shows the block diagram of the system and the nodes analyzed. In this SS I, SS II and SS III were each one of the rectifier substations. The nodes to be analyzed were Middle which is the connection point to the second rectifier substation, Source which is the Point of Common Coupling 1 and Source 1.

Full Load, BRK, and OFF are the three possible operation states of each rectifier substation . BRK means that the load is changing in that time lapse, this operation state is unique for each one of the substations ensuring that the system has different types of load variation [1].

1) *Low Variability Case:* Table I contains the operating states of each one of the rectifier substations.

In this case the load in the system is not high and the operation of the rectifier substations was in a stepwise form. There is only one load increase during the time window of 2 to 3 seconds in which there are two rectifier substations in operation but only one of them is at full load. Figure.5-6 shows the p.u voltage in Source and Middle. Figure.7(a),(b) shows the load currents in Middle. Figure.8 shows the FFT on Source 1. In this case, the lowest point in the voltage was 0.963 p.u in Source and 0.962 p.u in Middle. Distortions are there in the current waveform and for Source 1 current FFT, the THD was calculated and it was of 12.20%.

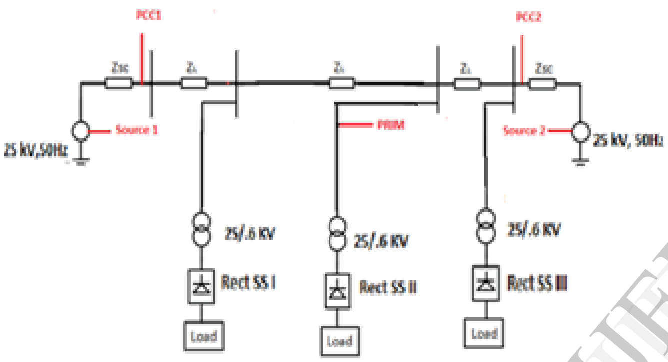

Fig. 4. Block Diagram

TABLE I

OPERATING STATS OF RECTIFIER SUBSTATIONS

Rectifier substation	0≤t(s) ≤1	1≤t(s) ≤2	2≤t(s) ≤3	3≤t(s) ≤4	4≤t(s) ≤5
SS I	BRK I	OFF	FULL LOAD	FULL LOAD	FULL LOAD
SS II	OFF	BRK II	OFF	OFF	OFF
SS III	OFF	OFF	BRK III	OFF	OFF

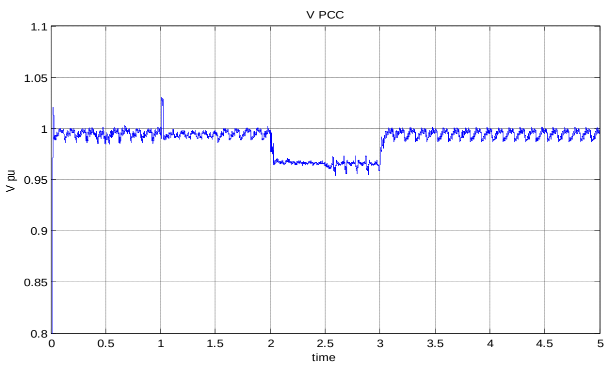

Fig. 5. PCC pu voltage

Both parameters are not within regulation; voltage drop is higher than 5% as the current THD also is higher than the 5% desired.

2) *High Variability Case*: The two main characteristics of the second case is a higher load in the system and the breaker movement at the rectifier substations is more irregular. Table II shows the operating states of each one of the rectifier substations in the 5 second time window of the simulation [1].

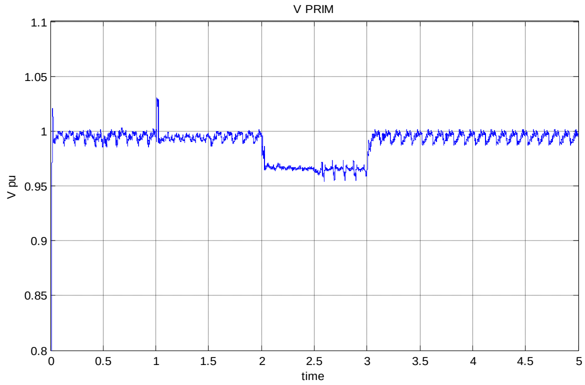

Fig. 6. PRIM pu voltage

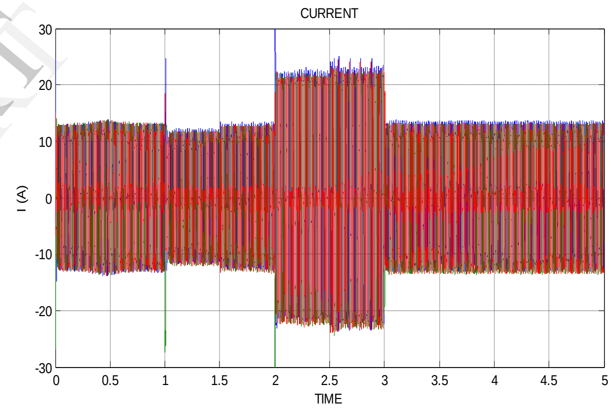

Fig. 7(a) load current variation

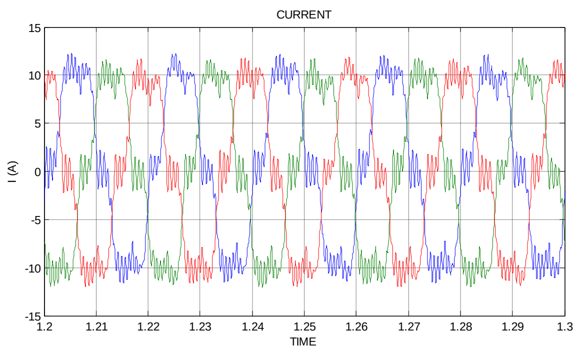

Fig. 7(b) Uncompensated load current

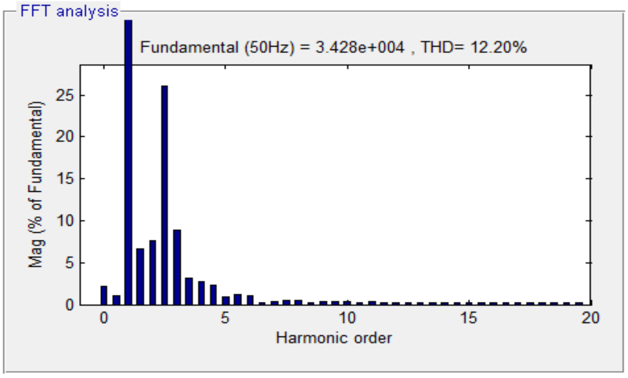

Fig. 8.Current FFT

TABLE II
OPERATING STATS OF RECTIFIER SUBSTATIONS

Rectifier substation	0≤t(s) ≤1	1≤t(s) ≤2	2≤t(s) ≤3	3≤t(s) ≤4	4≤t(s) ≤5
SEE I	BRK I	OFF	FULL LOAD	FULL LOAD	FULL LOAD
	0≤t(s) ≤2	1≤t(s) ≤2.5	2.5≤t(s) ≤3	3≤t(s) ≤4	4≤t(s) ≤5
SEE II	FULL LOAD	BRK II	OFF	BRK II	FULL LOAD
	0≤t(s) ≤2	2≤t(s) ≤2.4	2.4≤t(s) ≤3.1	3.1≤t(s) ≤4	4≤t(s) ≤5
SEE III	FULL LOAD	FULL LOAD	OFF	BRK III	FULL LOAD

In this particular case as the load in the rectifiers was higher wave distortion became clearer and voltage drop increased Figures 9- 12 shows the simulation results.

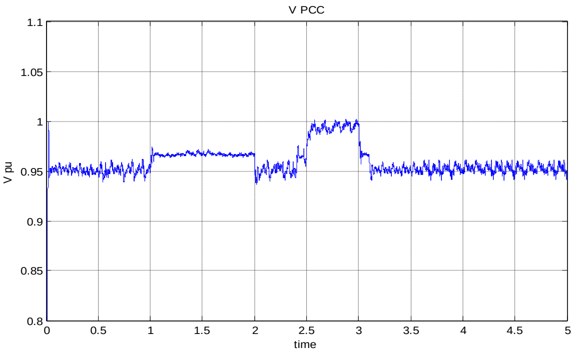

Fig. 9. PCC pu voltage

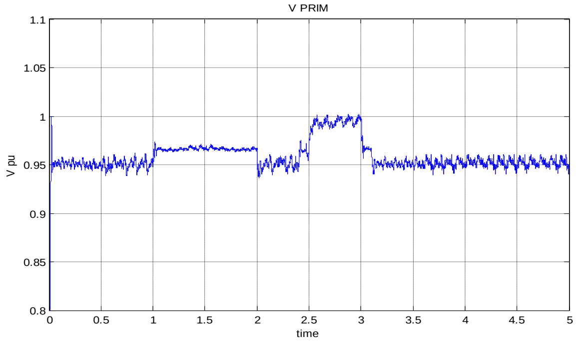

Fig. 10. PRIM pu voltage

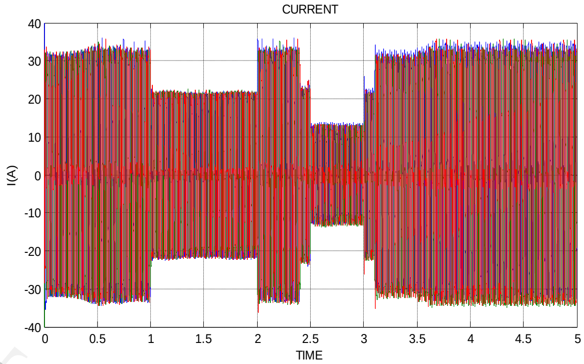

Fig. 11(a) load current variation

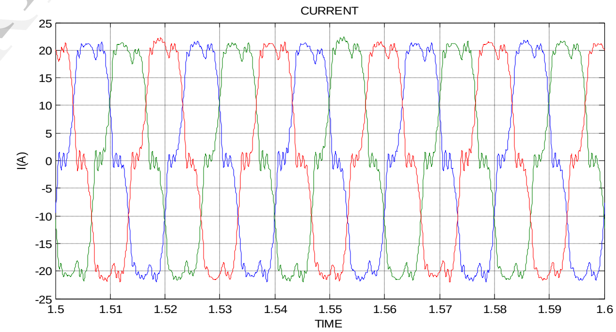

Fig. 11(b) Uncompensated load current

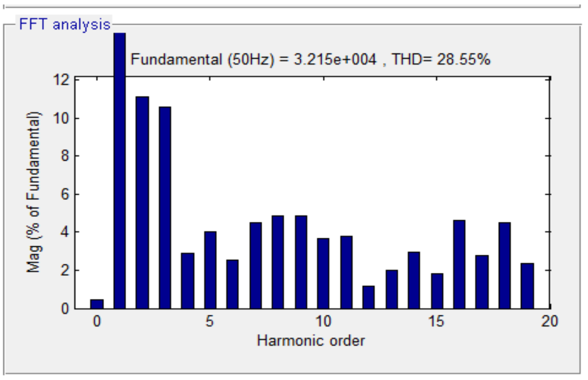

Fig. 12. Current FFT

A voltage fall of around 0.02p.u in the high variability case compared to the low variability shows the impact on the whole system due to the increase of the load

3) Implementing the effect of single traction load :

The speed characteristic of train is shown in Fig. 13.

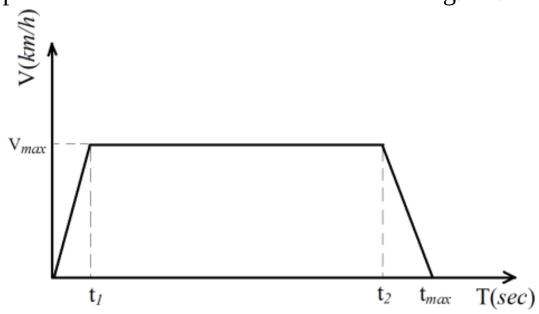

Fig. 13 Speed characteristics of the train sets with time variations

The train start moving from first station and with accelerating movement arrive to maximum speed after t1 seconds. Then, continue with the same speed until t2, then railway reduces its speed to stop at the second station at tmax.[9]

Table III contains the operating states of single traction load. Figure 14- 17 shows the simulation results.

After running these three cases it is clear what are the measures to take and the parameters to take into account. The SVC has to correct the voltage in all cases to achieve the desired regulation and the Harmonic filter designed has to correct the wave distortion.

TABLE III

Operating States of single traction load

Time	Rectifier substation SS I	Rectifier substation SS II	Rectifier substation SS III
0≤t(s) ≤1.5	Accelerating Speed	*No Load*	*No Load*
1.5≤t(s) ≤2.5	Constant Speed	*No Load*	*No Load*
2.5≤t(s) ≤3.5	*No Load*	Decelerating Speed	*No Load*
3.5≤t(s) ≤4	*No Load*	Stopped	*No Load*
4≤t(s) ≤5.5	*No Load*	Accelerating Speed	*No Load*
5.5≤t(s) ≤6.5	*No Load*	Constant Speed	*No Load*
6.5≤t(s) ≤7.5	*No Load*	*No Load*	Decelerating Speed
7.5≤t(s) ≤8	*No Load*	*No Load*	Stopped
8≤t(s) ≤9.5	*No Load*	*No Load*	Accelerating Speed
9.5≤t(s) ≤10	*No Load*	*No Load*	Constant Speed

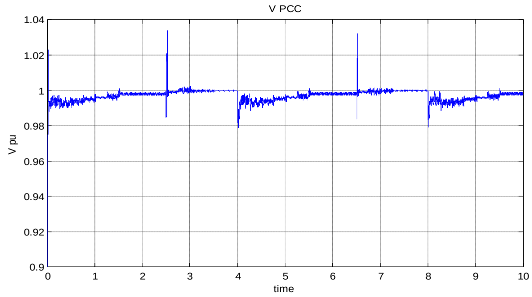

Fig. 14 PCC pu voltage

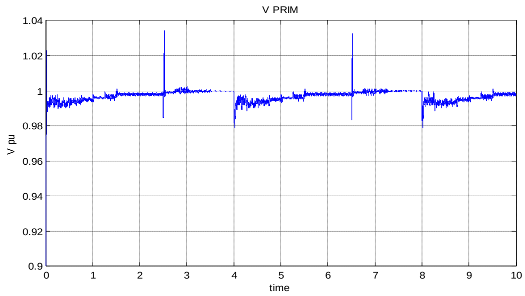

Fig. 15 PRIM pu voltage

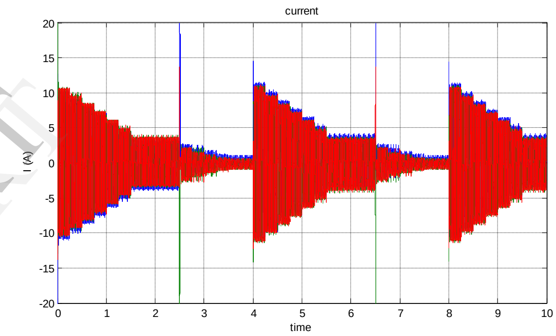

Fig. 16(a) load current variation

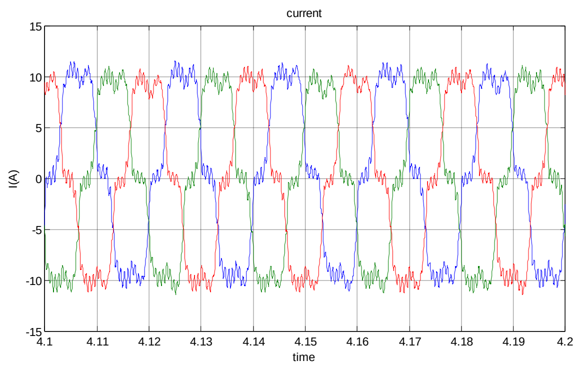

Fig. 16(b) load current variation

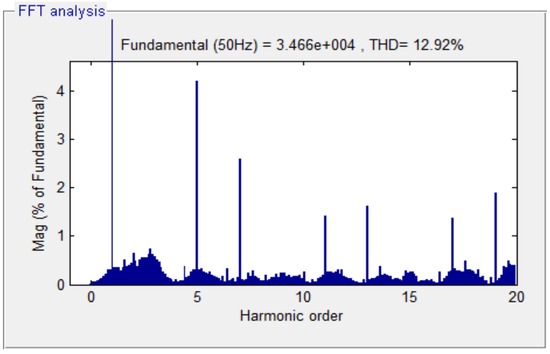

Fig.17. Current FFT

VIII. IMPLEMENTATION OF SVC AND FILTER

The Flexible AC Transmission Systems (FACTS) device offers accurate control over certain parameters of the network, thereby improving its operation. The main effect of the traction systems on the network is voltage drop, due to the behavior of the trains, which basically are seen by the grid as a variable load. The other problem is harmonic generation in the rectifier substations and their flow to the rest of the distribution system.

The voltage regulation goal was to achieve a maximum of 5.0% drop, based on Table 3-1 of the IEEE 141-1993[6], which is the allowed value for that voltage level in the United States. So the SVC control has to assure that the network satisfied these limits.

A filter was installed in the same point of the SVC in order to reduce wave distortion present on the network. Due to the characteristics of the rectifier substation the first important harmonic was the fifth so the R-L filter was tuned to reduce current THD below the 5% stated in the Table 10.3 of the IEEE 519-1992 [5].

In radial systems the compensation is better located at the end of the line, while in a two source system such as the one of the electric traction, compensation is best located at the midpoint [8]. This is why the SVC was connected in the PRIM point. The location of the SVC and the filter in the whole system is shown in Figure 18.

The SVC uses Mechanically Switched Capacitor-Thyristor Controlled Reactor (MSC-TCR). This option provides the capacitive support and it is cheaper than the TSC-TCR configuration. However, this alternative choice is not as efficient as using the SVC proposed for several reasons.

The main problem that FACTS devices have is that they are not cost competitive, particularly in terms of the initial investment. However, in the long run it might be a cheaper option because the SVC allows a larger and more efficient expansion of the network with better parameter control [8]

Figures 19-30 shows the simulation results with SVC and harmonic filter low variability, high variability and single traction load cases.

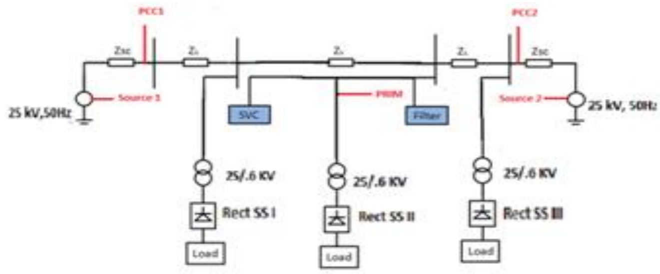

Fig. 18. Electric traction system with SVC and filter

1. *Low Variability Case*:

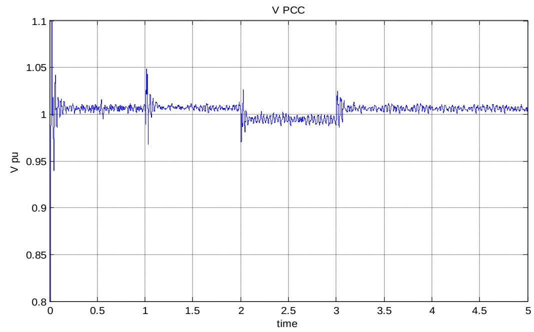

Fig. 19. PCC pu voltage

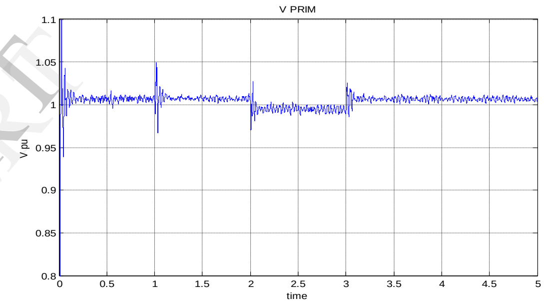

Fig. 20. PRIM pu voltage

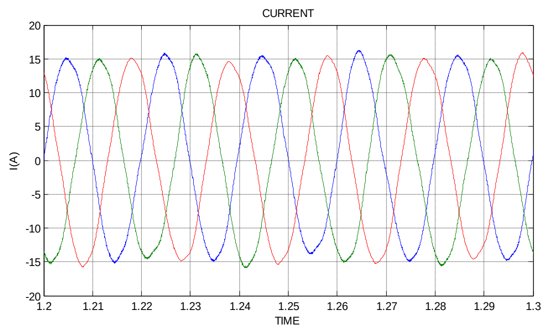

Fig. 21 Compensated load current

In improving the voltage, the lowest point in the low variability case went from around 0.963 p.u to 0.992 p.u in the worst case, improving voltage in 3.0%. In the high variability case voltage went from 0.942 p.u to 0.982 p.u in the worst case, showing an improvement of 3.5%. In single traction load condition voltage improved from 0.986 to .995. All the compensated cases satisfied voltage regulation.

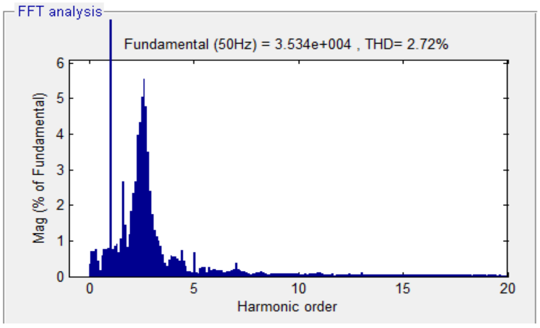

Fig. 22. Current FFT

2. *High Variability Case:*

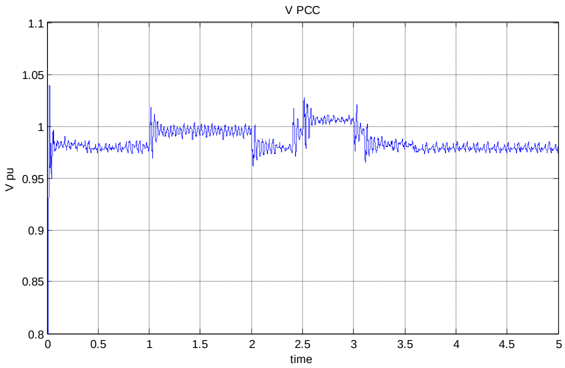

Fig. 23. PCC pu voltage

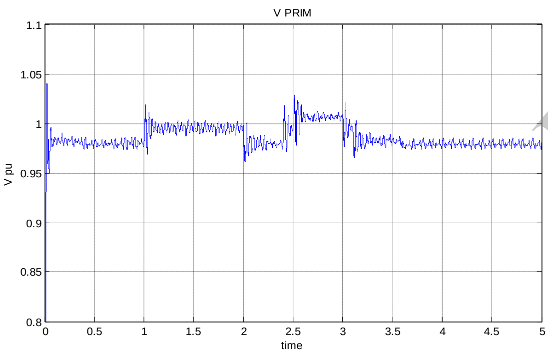

Fig. 24. PRIM pu voltage

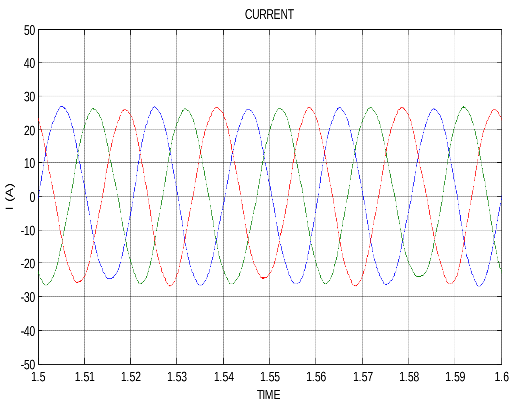

Fig. 25 Compensated load current

Without compensation the current THD in the source 1 was of 12.20% in low variability , 28.55% in high variability and 12.92% for single traction load. With the installed filter the current THD dropped to 2.72% in low variability , 3.71% in the high variability and 3.41% for single traction load .This shows that the filter installed successfully reduced wave distortion in the system and managed to lower current THD to desired regulate, below 5%, as it is stated by the IEEE 519-1992 Similarly the pu value of Voltage.

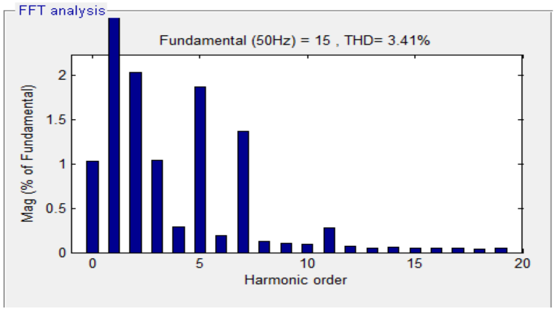

Fig. 26. Current FFT

3. *Single traction load case:*

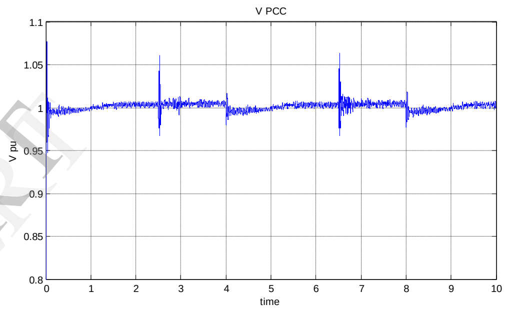

Fig.27 PCC pu voltage

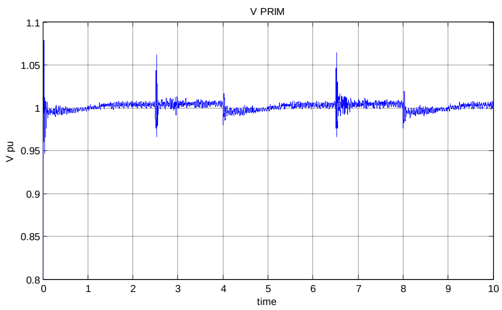

Fig. 28 PRIM pu voltage

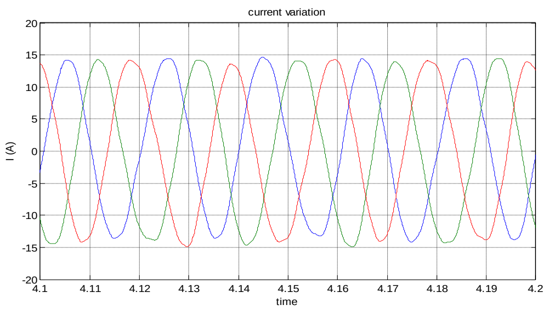

Fig. 29 compensated load current variation

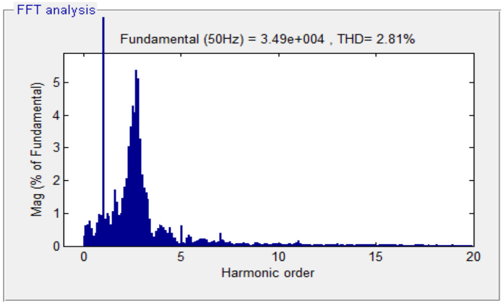

Fig. 30. Current FFT

IX. CONCLUSIONS

The main power quality problems were successfully replicated with the proposed model. The rectifier and load variability had the expected impact on the voltage drop, as well as current and voltage waveforms. The simulation results demonstrates that SVC is a reliable device that can handle a nonlinear behaving system such as the direct current electric traction.

Current distortion was also corrected with the filter installed with the SVC. The regulation objective was to have a current THD below 5% and in all cases, the values dropped to achieve regulation. The compensation showed that the SVC is an effective device that can adapt to different conditions present in the system; it can handle situations in which there is an irregular power demand and wave distortion problems can be solved using a filter along with the compensator.

X. FUTURE WORK

The effect of Static VAR Compensators (SVC) and harmonic filter can be studied by changing the load to AC traction loads. The compensations can be compared from the simulation results.

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