Reactive power and harmonic distortion control in electric traction systems

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Reactive Power and Harmonic Distortion Control in Electric Traction Systems

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Abstract—Electric traction systems generate various power quality problems that have an important impact on its distribution network. In this paper a DC electric traction system was modeled in order to generate the problems that its operation implicated. Once the power quality phenomena were replicated a compensation device, SVC, was added to the distribution network to improve voltage and also a filter was installed in the same node to reduce wave distortion. Finally the possible events that can appear if the original configuration of the compensator device is changed are 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

Electric traction systems have been acquiring momentum in the nowadays transportation sector. Since the beginnings of last century they have been a preferred option due to their high performance, low maintenance cost, and lack of greenhouse-gas emissions [1] [2].

The AC and DC traction systems can generate disturbances to the power quality. In AC based systems the voltage unbalance is the main problem [3], while in DC the harmonic generation must be taken into account. Harmonic distortion appears in this type of traction systems due to the presence of the rectifier substations in the network [4] [1].

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 [5].

This paper shows a DC electric traction model with 3 rectifier substations, a 7.5km transmission line and a 2 source feeding system of 34.5kV. 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 two cases were designed to analyze it: one in which the load and the variability were high and its counterpart of low load and variation. The system was modeled in the software PSCAD (Power System CAD) due to the fact that it has enough tools to analyze power quality problems with power electronic devices.

In section III a Static Var Compensator (SVC) and a filter are added to the system to correct the power quality problems generated and evaluate the flexibility of the compensation.

Finally an alternative option to the original SVC configuration is evaluated and the problems that it would implicate are listed.

II. DC TRACTION SYSTEMS

The system that it is going to be analyzed and compensated is a direct current electric traction system. Figure 1 shows the typical feeding scheme. Starting from the high voltage grid, two substations are connected to each other 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 [6].

![Fig.1. DC Electric Traction Feeding Scheme](image)

Power is fed to the vehicle through a conductor cable connected to the catenary system. Nowadays most transportation systems function with standardized voltage levels of 600V to 750V [6], in this particular case the catenary system will feed the vehicle at 750V.

A. Power Quality Problems

Electric transport systems have power electronic devices which have a direct impact on the normal operating conditions and the behavior of certain components in the presence of contingency situations. The power quality phenomena that can
appear are: voltage fluctuations, voltage and current distortion, voltage sags, voltage transient, and voltage and current unbalances [7]. It is important to point out the fact that all of the phenomena mentioned above appear in cases in which there is a 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 rectifier substation is an additional component in the DC electric traction system that generates a key problem to the network. 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 [8]. Direct current electric traction systems do not have just one rectifier substation; in this particular example three rectifier substations are supposed, in larger systems there can be more rectifiers.

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.

III. MODELING AND SIMULATION OF THE SYSTEM ON PSCAD

The main feeding system modeled was with two 34.5kV sources connected to a 7.5km line. Each one of the sources had a 100MVA short circuit equivalent and the transmission line was divided into three stages of 2.5km each. An AWG 4/0 conducting wire was assumed for the transmission line. In each one of the stages a rectifier substation was installed. Each one of them had a transformer with a 34.5/0.6kV 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. Through this factor the feeding voltage was calculated in order to achieve the 750V desired.

To be able to simulate the load variability that the system would have, each substation had 3 breakers which were programmed to switch on or off. 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.

A. Study Cases

To analyze the system, and the power quality problems generated two scenarios were created; one with high variability of the load and one with more of a stepwise variation. The purpose of these examples is to recreate 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. Figure 2 shows a diagram of the system implemented on PSCAD and the nodes analyzed. In this figure, $Z_{SC}$, is the short circuit impedance equivalent, $Z_L$, the transmission line impedance for that transmission line segment, and SEE I, II and III were each one of the rectifier substations. The nodes to be analyzed were 2PRIM which is the connection point to the second rectifier substation, PCC1 which is the Point of Common Coupling 1 and Source 1.

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 different 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. Figures 3-5 show the p.u voltage in PCC1 and 2PRIM as the FFT on Source 1.

In this case, the lowest point in the voltage was 0.946p.u in PCC1 and 0.945p.u in 2PRIM. For Source 1 current FFT, the THD was calculated and it was of 24.07%. 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 second case designed has two main characteristics: 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.

<table>
<thead>
<tr>
<th>Rectifier Substation</th>
<th>0≤t(s)≤1</th>
<th>1≤t(s)≤2</th>
<th>2≤t(s)≤3</th>
<th>3≤t(s)≤4</th>
<th>4≤t(s)≤5</th>
</tr>
</thead>
<tbody>
<tr>
<td>SEE I</td>
<td>BRK I OFF</td>
<td>FULL LOAD</td>
<td>FULL LOAD</td>
<td>FULL LOAD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0≤t≤2</td>
<td>1≤t≤2.5</td>
<td>2≤t≤3</td>
<td>3≤t≤4</td>
<td>4≤t≤5</td>
</tr>
<tr>
<td>SEE II</td>
<td>FULL LOAD</td>
<td>BRK II OFF</td>
<td>BRK II FULL</td>
<td>LOAD</td>
<td></td>
</tr>
<tr>
<td></td>
<td>0≤t≤2</td>
<td>2≤t≤2.4</td>
<td>2.4≤t≤3.1</td>
<td>3≤t≤4</td>
<td>4≤t≤5</td>
</tr>
<tr>
<td>SEE III</td>
<td>FULL LOAD</td>
<td>FULL LOAD</td>
<td>OFF BRK III FULL LOAD</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In this particular case as the load in the rectifiers was higher wave distortion became clearer and voltage drop increased. Figures 6-10 show the simulation.

The biggest difference between the two cases is the voltage drop that the system suffers. A voltage fall of around 0.022 p.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.

After running these two 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 both cases to achieve the desired regulation and the filter designed has to correct the wave distortion.

**IV. ELECTRIC TRACTION SYSTEM COMPENSATED**

The basic DC electric traction system impacts different aspects in the power system that is connected with the previously mentioned problems. One way to correct these...
phenomena is through power electronics. Devices as the Flexible AC Transmission Systems (FACTS) offer the possibility to acquire an important control over certain parameters of the network, thereby improving its operation. The main effect that traction systems have 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[9], 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.

To reduce wave distortion present on the network a filter was installed in the same point of the SVC. 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 [8].

The first issue to address was the location of the compensator. 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 [10]. This is why the SVC was connected in the 2PRIM point. The location of the SVC and the filter in the whole system is shown in Figure 11.

The SVC proposed has a Static Var Generator (SVG) configured with a two branch Thyristor Switched Capacitor (TSC) and a Thyristor Controlled Reactor (TCR) and the control loop was set to have a 3% allowed regulation slope.

A. Compensated Study Cases

Once compensated the two designed cases were tested to verify the proper voltage compensation and the harmonic correction. Figures 12-19 show the evaluated parameters on the same nodes as before to analyze the changes in the network in presence of the SVC and the filter with both load variability cases to evaluate the flexibility of the compensation.

![Fig. 11. Electric Traction System with SVC](image)

![Fig. 12. Compensated PCC1 p.u Voltage](image)

![Fig. 13. Compensated 2PRIM p.u Voltage](image)

![Fig. 14. Compensated Source 1 Current FFT](image)

![Fig. 15. Compensated PCC1 Voltage Waveform](image)
The two parameters that were being studied with the compensation improved and achieved regulation, giving support to the different scenarios that the system could upfront.

TABLE III
LOW AND HIGH LOAD VARIABILITY COMPARATIVE RESULTS

<table>
<thead>
<tr>
<th>Node</th>
<th>Low Variability</th>
<th>Compensated Parameter Value</th>
<th>Low Variability</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCC1</td>
<td>0.946p.u</td>
<td>0.975p.u</td>
<td></td>
</tr>
<tr>
<td>2PRIM</td>
<td>0.945p.u</td>
<td>0.975p.u</td>
<td></td>
</tr>
<tr>
<td>THD Source1</td>
<td>24.07%</td>
<td>3.44%</td>
<td></td>
</tr>
</tbody>
</table>

Analyzing Table III of the given cases with and without compensation, the effectiveness of the compensator can be evaluated. In improving the voltage, the lowest point in the low variability case went from around 0.945p.u to 0.975p.u in the worst case, improving voltage in 3.0%. In the high variability case voltage went from 0.922p.u to 0.957p.u in the worst case, showing an improvement of 3.5%. Both compensated cases satisfied voltage regulation.

Without compensation the current THD in the Source 1 was of 24.07% in the low load variability and 22.64% in the high variability. With the installed filter the current THD dropped to 3.44% in low variability and to 4.26% in the high variability. This shows that the filter installed with the SVC successfully reduced wave distortion in the system and managed to lower current THD to the desired regulation, below 5%, as it is stated by the IEEE 519-1992.

V. IMPLICATIONS OF USING A MSC-TCR STATIC VAR GENERATOR TO COMPENSATE THE ELECTRIC TRACTION SYSTEM

One alternative solution that can be suggested for the Static Var Generator (SVG) of the SVC is the use of a 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 MSC-TCR configuration does not have the response or the repeatability of operation generally needed for the dynamic compensation of systems such as the one addressed. Another issue is the fact that the response of mechanical breakers employed to switch the capacitors will determine mostly the elapsed time between the capacitive var demand and the actual capacitive var output. Also precise and constant control of the mechanical breaks switch control is not possible because the capacitive bank must be switched without any appreciable residual charge to avoid high and possibly transient generation. As a consequence, whenever the capacitor is switched out it is discharged before the next switching takes place. Considering a practical discharge time of 3-4 cycles, a typical breaker closing time of about 3-7 cycles the MSC delay may be 6-11 cycles. This means that in a 60Hz system like the one implemented the operation can fluctuate between 0.1 and 0.1833 seconds, which is considerable based on the dynamic nature of the system [10], [12].

The typical life of a breaker is of 2000 to 5000 operations, this implies that depending on the variability of the system periodic repairs are necessary [10]. On the other hand, FACTS devices provide several benefits in comparison with the previous alternative. These devices have the ability of rapid and precise switching in and out of large capacitor banks. This is made possible by solid state switches like the thyristor bidirectional valve. This device is able to operate orders of
magnitude faster, more precise, and more reliable than its mechanical switching counterpart. Additional to these operational characteristics they give the possibility to control phase angle, impedance, voltage and current in ways that would not be possible with mechanical breakers switching. [10], [6].

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 [10].

The alternative to the TSC with MSC brings a new set of events on the system that can easily be avoided by the use of the thyristor valve; such is the case of transient generation, slower response and limited control action. Based on these reasons the replacement of the TSC by an MSC for cost reduction is not a good option due to the behavior of the system. In constantly changing systems, the fact that the speed of response is harmed directly affects the quality of the compensation because it will slow down the correction of the voltage along the feeding line.

VI. CONCLUSION

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 study cases designed generated certain “randomness” in the power demand throughout the system. In the low variability case, voltage compensation was of 3.0% to regulate the system to the desired values. With no change in the SVC configuration or control loop and an increase in the load and its variability caused a compensation raise to 3.5%. This demonstrates that it is a reliable device that can handle a non-linear 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 both cases, high and low variability values dropped to achieve regulation. In one case current THD values went from 24.07% to 3.44% and in the other from 22.64% to 4.26%, showing an improvement in wave distortion.

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.

VII. FUTURE WORK

Custom Power devices represent another alternative to compensate the proposed model. They can be connected series, shunt or a combination in the system and they correct the power quality problems that this model generates [11]. The Unified Power Quality Conditioner (UPQC), which is an integrated series and shunt active filter, could be studied to analyze its impact on the electric traction model proposed.

REFERENCES

VIII. BIOGRAPHY

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