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MITIGATION OF VOLTAGE FLICKER BY SUPERCONDUCTING SYNCHRONOUS CONDENSER (SUPERVAR)

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***Summary*: Voltage flicker caused by the electric arc furnace (EAF) and the mitigation using the superconducting synchronous condenser (SuperVAR) by the American Superconductor Corp. are considered in this paper. The modeling of EAF, SuperVAR and the system used are discussed. Fast reactive power support to reduce voltage flicker problem by an EAF is desirable. The voltage fluctuation amplitude is used as an index to evaluate the effectiveness of SuperVAR for two different MVar levels. At the PCC (point of common coupling) bus, the application of the SuperVAR can improve the voltage flicker by 6% and 19% by applying DC1A type and AC4A type exciter to the SuperVAR. With an DC1A type exciter, the SuperVAR can output only between +1 and -2 MVAR and with an AC4A type exciter the SuperVAR can provide its full rated power (8MVAR) to the system, making the voltage flicker a less severe.**

Key words:
Superconductivity
Synchronous condenser
Voltage flicker
Power quality

1. INTRODUCTION

TVA (Tennessee Valley Authority) has launched a project with the American Superconductor Corp. to build a superconducting synchronous condenser to reduce the voltage flicker caused by electrical arc furnace (EAF). The operation of the EAF causes random pulsing power consumed from the network, therefore the voltage would fluctuate. The term flicker is derived from the impact of the voltage fluctuation on lamps such that they are perceived to flicker by the human eye . Typically, magnitudes as low as 0.5% can result in perceptible lamp flicker if the frequencies are in the range of 6 to 8 Hz [1]. To alleviate this rapid change of voltage fluctuation, a device can be designed to compensate the reactive power to the system, therefore reducing the flicker magnitude. SuperVAR [2] is designed to achieve this goal. A system study was performed to determine the impact of SuperVAR on the voltage flicker problem.

This paper first presents some unique characteristics of the SuperVAR. Then the simulation models of EAF and SuperVAR are discussed. The reduced system model in PSCAD/EMTDC is built from the TVA system model, which is in PSS/E format. The effectiveness of the SuperVAR is evaluated by looking at the voltage fluctuation amplitude caused by the operation of EAF.

2. SUPERVAR CHARACTERISTICS

The SuperVAR is designed by the American Superconductor Corp. The design is based on the conventional technology of synchronous condenser by replacing the rotor windings with high temperature superconductor (HTS) coils. Fig 1 shows the schematic layout of a SuperVAR machine.

Some main characteristics of the SuperVAR machines are listed as following [3, 4]:

- Low synchronous reactance due to large effective airgap
- Effectively zero field winding loss yields high efficiency
- Absence of iron teeth on the stator eliminates major sources of harmonics and losses
- Fast reacting transient dynamic voltage support and stability
- Continuous steady state operation
- Fully capable of either leading or lagging VAR mode
- Low maintenance and high reliability
- Fast and easy installation
- Operation on line voltage on the low side of transmission to distribution transformer
- Recover voltage without any change in machine's field excitation

A photo of the unit delivered to TVA is shown in Figure 2.

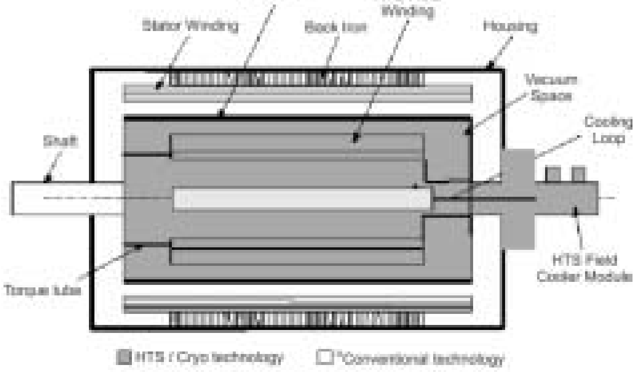

Fig. 1. An high-temperature-superconducting (HTS) machine configuration

Fig. 2. The SuperVar Unit delivered to TVA

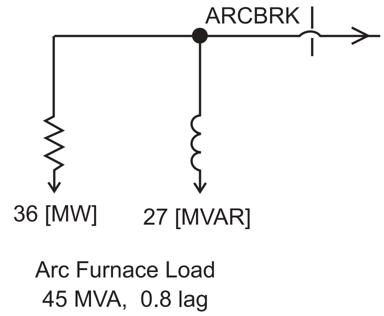

Fig. 3. Electric arc furnace model

As the photo shows, the SuperVAR system (rotating machine and all auxiliary systems) is packed in an enclosure, which minimizes on-site installation. In addition, the system fits in an 20-foot trailer providing high mobility.

3. SIMULATION MODELS

The current TVA system model does not include the electric arc furnace and SuperVAR models. Modeling of these two components and the nearby power system are discussed in this section.

Electric arc furnace (EAF)

Electric arc furnace models can be very complicated due to the random and chaotic nature of the melting process [5]. In this study, we use a simple model to represent the EAF in the simulation, where a constant real and reactive power load is connected with a timed switch, as shown in Fig 3. Similar modeling approaches can also be found in ink [6]. Another simple modeling method is to have a timed-fault in parallel with the constant-power loads.

The rating of the arc furnace is 45 MVA. With the power factor of 0.8, the active power of the arc furnace is 36 MW and the reactive power is 27 MVAR. In addition, from TVA measurement data, the switching on and off typically occurs between 2-7 Hz in frequency range. For this study, we turn on and off the switch using 0.1 second intervals (5 Hz) to simulate the operation of EAF.

SuperVAR

SuperVAR acts like a synchronous condenser; therefore, we use the synchronous machine model to represent SuperVAR for this study. The parameters are characterized by the American Superconductor Corp. and are provided to us as follows:

- Line voltage: 13.8 kV
- Power factor: 90^o lead or lag
- Phase current: 326 A
- field current: 160 A (at 8MVAR lagging power factor)
- X_d (unsaturated *d* axis reactance) (pu): 0.422
- X_q (unsaturated *q* axis reactance) (pu): 0.423
- X_d' (unsaturated *d* axis transient reactance) (pu): 0.223
- X_q' (unsaturated *q* axis transient reactance) (pu): 0.223
- X_d" (unsaturated *d* axis subtransient reactance)(pu): 0.126
- X_q" (unsaturated *q* axis subtransient reactance) (pu): 0.126
- T_{do}' (unsaturated *d* axis transient open-circuit time constant) (sec): 857
- T_{qo}' (unsaturated *q* axis transient open-circuit time constant) (sec): None (No field winding on q-axis)
- T_{do}" (unsaturated *d* axis subtransient open-circuit time constant) (sec): 0.184
- T_{qo}" (unsaturated *q* axis subtransient open-circuit time constant) (sec): 0.407
- *Ra* (armature resistance) (pu): 0.005
- *H* (inertia constant) (sec): 1.55
- *D* (speed damping factor): 10.6 N-m/radian.

The exciter of the SuperVAR is taken from a similar rating synchronous condenser, which is either a DC1A or AC4A model. Detailed descriptions of the models can be found in [7].

Simplified system model in PSCAD/EMTDC

T_{do}' for a SuperVAR, is very large. In PSS/E, it sets a limit on T_{do}' within 1 and 10 seconds. Therefore we then pursue the simulation in PSCAD/EMTDC. However we do not have the system model in PSCAD/EMTDC, so to constructed a simplified system model for this particular interest.

To construct the model in PSCAD/EMTDC, we first had to determine how large a portion of the system to model. We derived the regional model from the TVA system in PSS/E and found the buses at which the voltage fluctuation exceeds 0.15% from the initial states when only the arc furnace is operating, and where the voltage fluctuation at the arc furnace bus is at 3%. There are 52 buses remaining in the PSCAD model.

The simplified buses are shown in the circled area in Figure 4.

At boundary buses, where they are connected to the rest of the TVA system, were place equivalent loads and voltage sources to represent the total power flowing between the boundary bus and adjacent buses (excluding the bus connected to the reduced system). The power flows can be found in the PSS/E, where the static system solution is found. This is to ensure that the steady state of the equivalent network is preserved.

All the transmission lines are represented as the simplified π model, as in PSS/E. The resistance and reactance are converted from per unit values to normal values (Ohm, Hen-

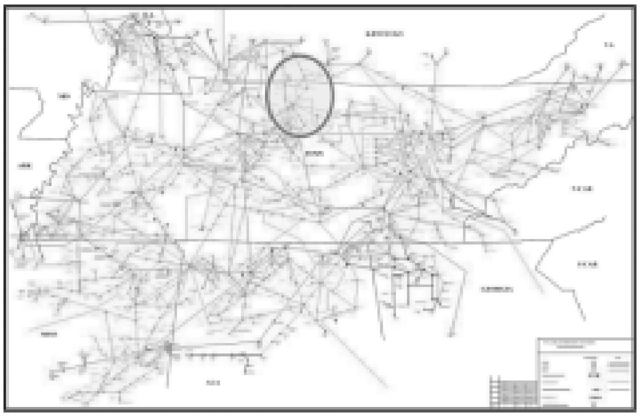

Fig. 4. Simplified PSCAD model coverage area

ry, and Coulomb). The simplified model is comprised of 52 buses, mainly 161kV buses. Among them, there are 4 transformers, 8 generators (all in the Gallatin, Tennessee area), 44 loads (active & reactive) and 42 transmission lines and 11 external connecting buses (with equivalent loads).

EAF and SuperVAR connection

The EAF and SuperVAR are connected to the 161 kV system via a step-up transformer (161kV/38kV) as shown in Figure 5.

4. TIME CONSTANT DISCUSSION

As mentioned previously, T_{do}'= 857 seconds. The PSS/E data validation process prohibits inputs from such large numbers for synchronous machines. In PSCAD, we can specify any T_{do}' to run the simulation. Larger T_{do}' takes longer time for the power output from the SuperVAR to achieve the steady state in the simulation, as shown in Figure 6. In Figure 6, the switching of the EAF load starts at 50 seconds. In addition, when the EAF starts operating, it takes more cycles for the bus voltage fluctuation to come to a steady-state condition. For example, when T_{do}' = 857 seconds, the simulation must run for at least 700 seconds to start seeing the stable varying voltage fluctuation. For these reasons, the simulation period is lengthen for larger T_{do}'.

The steady state value of power and voltage patterns, however, do not change because of the changing of T_{do}'. In addition, the voltage fluctuation at PCC bus, as presented in Figure 7, does not change dramatically by choosing different T_{do}'. So it is not practical, from the simulation point of view, to wait for a long period of time before any switching can be introduced in the system. The typical value for T_{do}' is suggested in [8] ranges from 1 to 10 seconds. Therefore, in all the following simulations, T_{do}' is selected as 5 seconds instead of 857 seconds.

5. SIMULATION RESULTS

Base Case

When only the EAF is operating, the voltage fluctuations at the EAF bus and its PCC (point of common coupling) bus are shown in Figure 8 and Figure 10. In addition, the operation state of the EAF is shown in Figure 9.

The bus voltages drop when the EAF load is connected to the system and rise when the EAF load is off. Voltage fluctuation is most severe at nearby buses. The voltage fluctuation percentage can be defined as the peak-to-peak voltage amplitude difference divided by the steady state value before the EAF switching incipient. The fluctuation at the EAF bus is 6.3% and 1.1% (at the PCC bus). As mentioned in section I, 1% of voltage amplitude flicker and 5Hz of variation could be perceived by the human eye.

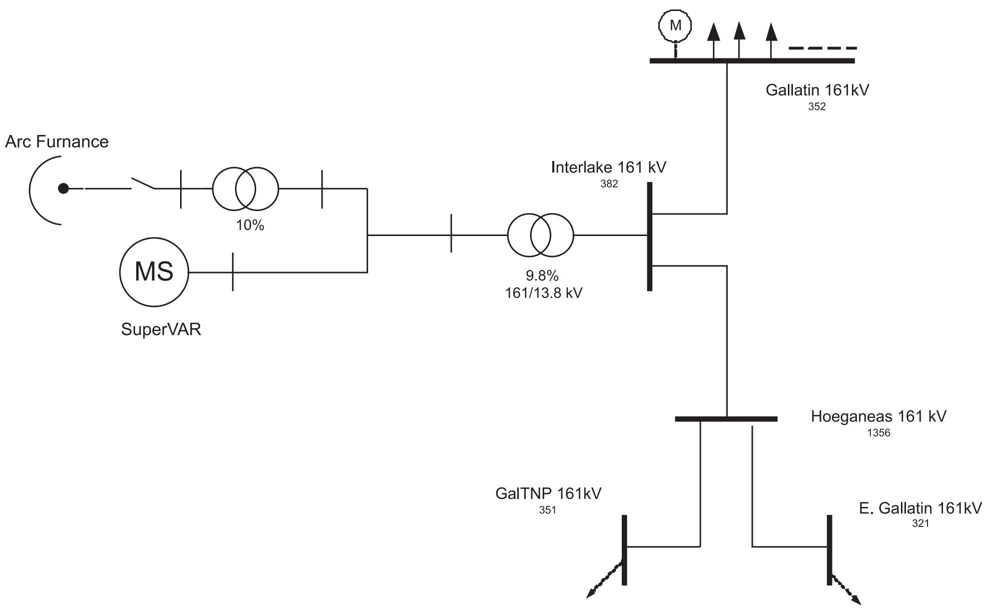

Fig. 5. Electric arc furnace and SuperVAR connected to Interlake 161kV and neighborhood buses

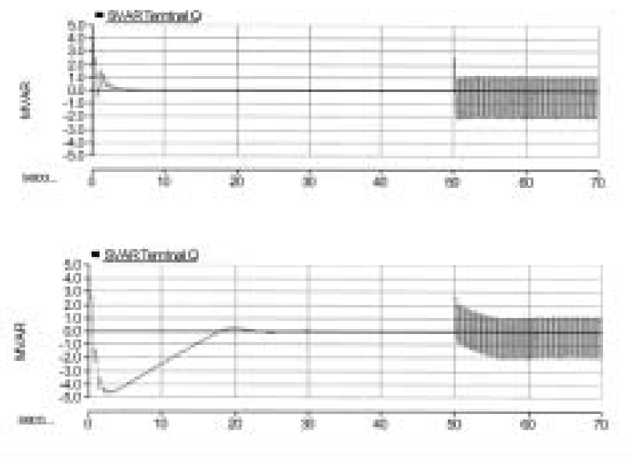

Fig. 6. Reactive power output from SuperVAR with EAF operating by using different T_{do}'. *Top*: T_{do}'=100 s, bottom: T_{do}'=5 s

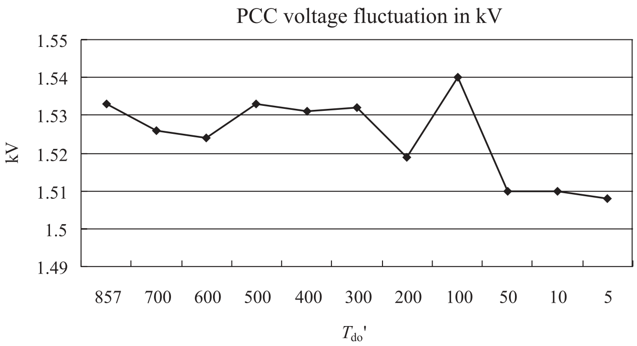

Fig. 7. PCC voltage fluctuations of different T_{do}'

6. SUPERVAR ONLINE

A rated 8MVA SuperVAR was introduced into the system, and the voltage fluctuations become less, as shown in Figures 11 and 12. The voltage fluctuation at the PCC bus drops to 0.98% and 5.6% at the EAF bus. The improvements are about 6% and 10% at the PCC and EAF bus, respectively. The output reactive power from SuperVAR, as shown in Figure 13, ranges between +1 and -2 MVAR, where 1 MVAR is injected into the system when the EAF load is connected and 2 MVAR is absorbed from the system when the EAF load is off-line. This provides alleviation on both directions of voltage fluctuations. Also, as the bus voltage drops rapidly, the SuperVAR can provide instant reactive power injection to the system.

The exciter in this section was taken from a typical exciter with the same MVA rating machine as in the TVA system, which is a DC1A type. As Fig 13 shows the output reactive power from the SuperVAR is only between +1 to -2 MVAR, so there is room for outputting more power from the machine. In the DC1A exciter control model, the field voltage via rate feedback is fed to the exciter's input to provide excitation system stabilization. So the change of the reactive power will be limited by the change of the terminal voltage.

To maximize the benefit from the SuperVAR, in other words, to output more VARs from the SuperVAR, we can change the exciter control. If we replace the exciter model to AC4A, which does not have the rate feedback from the field voltage, the SuperVAR would be able to output its rated reactive power (8MVA) to the system, as shown in Fig 14. The voltages at the EAF and PCC buses are shown in Fig 15 and Fig 16.

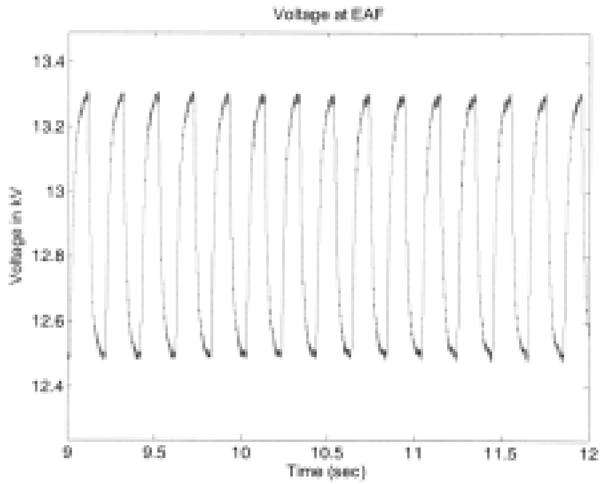

Fig. 8. Voltage at EAF bus when only EAF is operating

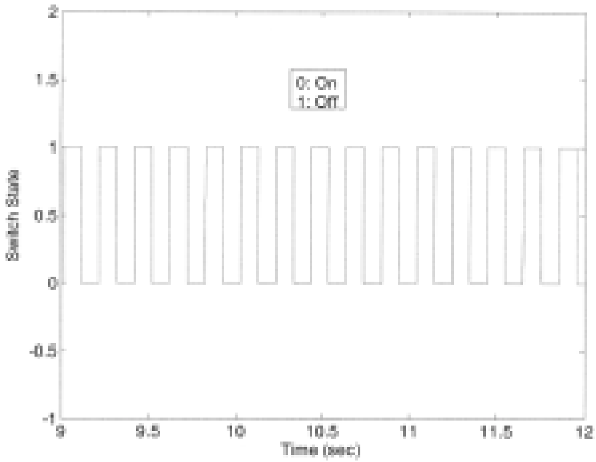

Fig. 9. Simulated EAF operation

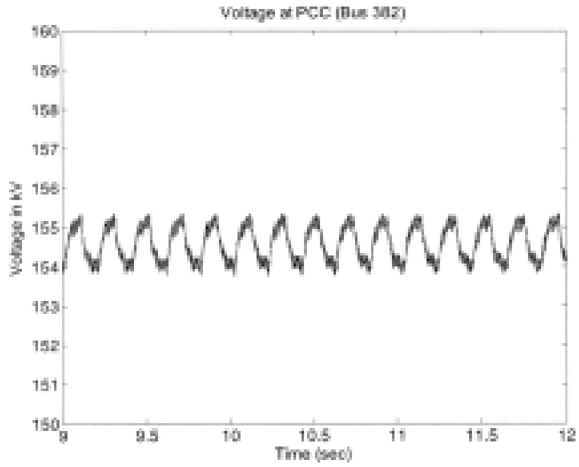

Fig. 10. Voltage at the PCC bus from EAF operation

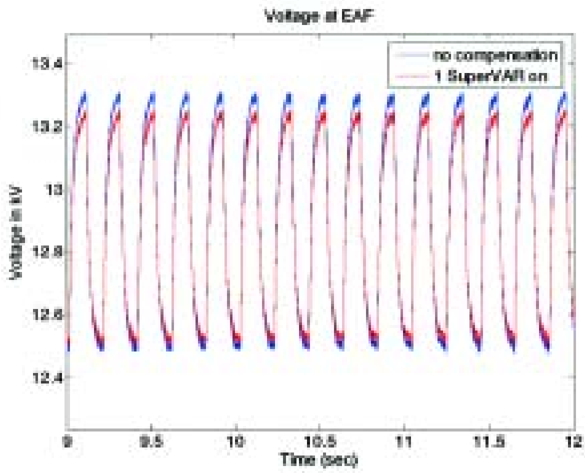

Fig. 11. Voltage at EAF bus when both SuperVAR and EAF are operating

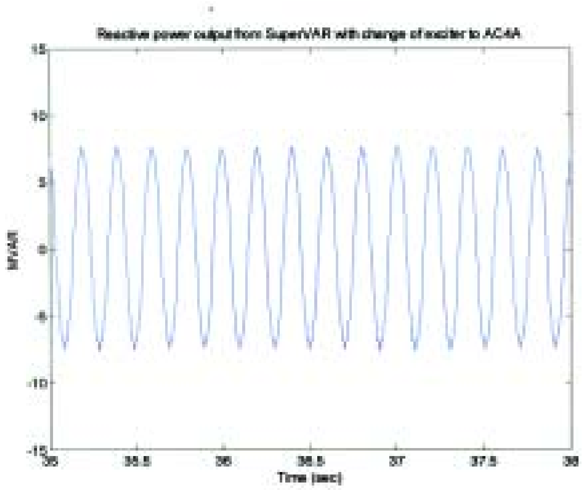

Fig. 14. Reactive power output from 1 SuperVAR with the new exciter (change from DC1A to AC4A)

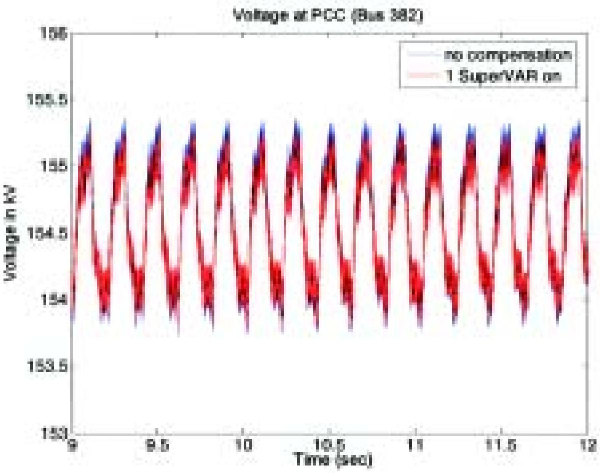

Fig. 12. Voltage at PCC bus when both SuperVAR and EAF are operating

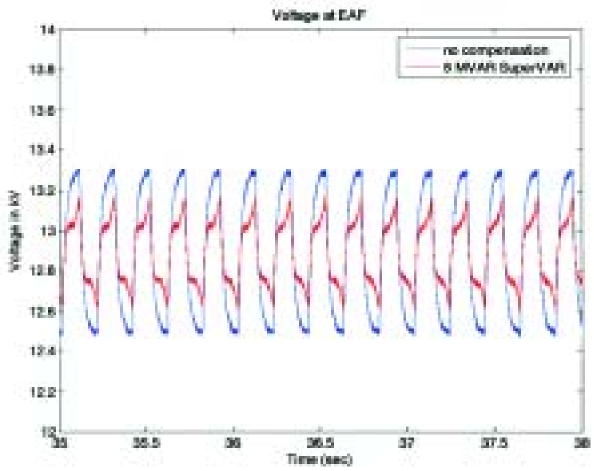

Fig. 15. Voltage at EAF bus when both 8 MVAR SuperVAR and EAF are operating

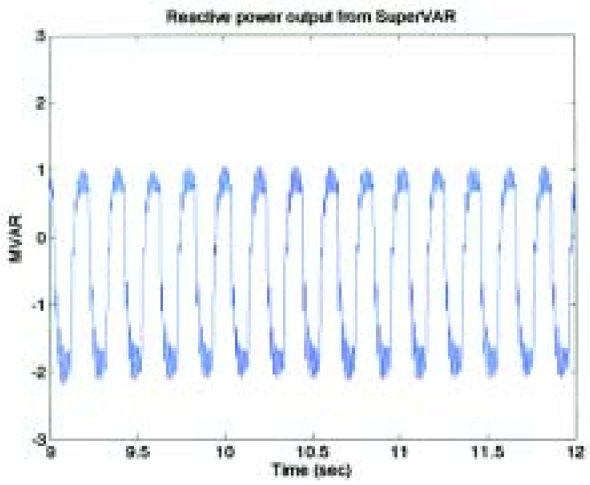

Fig. 13. Reactive power output from 1 SuperVAR

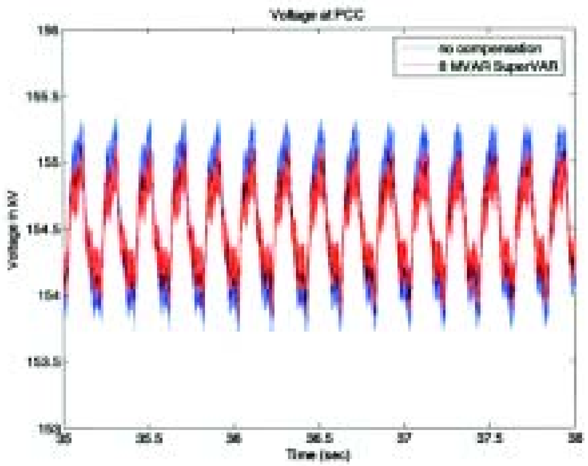

Fig. 16. Voltage at PCC bus when both 8 MVAR SuperVAR and EAF are operating

As expected, the more reactive the power outputs from SuperVAR, the less the voltage fluctuates. The voltage fluctuations drop to 4.4% and 0.85% at EAF and PCC buses, respectively, which could translate to 31% and 19% improvement from no SuperVAR compensation.

7. CONCLUSION

This study presented the modeling of the electric arc furnace (EAF), a superconducting synchronous condenser (a.k.a. SuperVAR), and a regional system to study the voltage flicker problem.

With no reactive power compensation provided, the voltage fluctuations induced by cyclic EAF operation are about 6.3% and 1.1% at the EAF and PCC (point of common coupling) bus, respectively. If a SuperVAR with a DC1A type exciter providing +1 and -2 MVAR is used, the voltage fluctuates by 5.6% at the EAF bus and by 0.98% at the PCC bus, which translate to 10% and 6% improvement. Further, if the exciter is changed to AC4A type to provide full rated power (8MVAR), the voltage fluctuation drops to 4.4% at EAF bus and 0.85% at PCC bus. This translates to 31% and 19% improvement from the no compensation case.

The study presented here is preliminary and the SuperVAR machine and its control parameters may have been modified since these results were pointed. Reactive power (VAR) injection alone is not sufficient to correct voltage angle and real power oscillations. Dynamic energy storage system is required to achieve good compensation to minimize the oscillations caused by real power fluctuations in an arc furnace.

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