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EAF Voltage Flicker Mitigation By FACTS/ESS

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Abstract--**One of the problems caused by an electrical arc furnace (EAF) is voltage fluctuation from the variations of the active and reactive furnace load, which are known as voltage flickers. In this paper, voltage flicker mitigation results by different FACTS and energy storage systems (ESS) were presented. The system X/R ratio looking from the point of common coupling, which has a special impact on the effectiveness of active compensation, was discussed. The study has clarified the misunderstanding of how the system X/R ratio should be calculated. The study showed that FACTS with ESS could play a better role than reactive power alone in mitigating EAF voltage flickers.**

Index Terms-- **electric arc furnace, voltage flicker mitigation, FACTS, energy storage systems.**

I. INTRODUCTION

An electrical arc furnace (EAF) changes the electrical energy into thermal energy by electric arc in melting the raw materials in the furnace. During the arc furnace operation, the random property of arc melting process and the control system are the main reasons of the electrical and thermal dynamics. That will cause serious power quality problems to the supply system [1].

The fundamental component of the current drawn by an EAF produces fluctuations of the voltage in the nearby distribution system. These fluctuations are the reasons of the phenomenon known as flicker. The voltage changes as much as 0.3~1% with frequencies between 2 and 8 Hz [2,3].

Building new lines, installing new and bigger transformers, or moving the point of common coupling to a higher voltage level are the traditional methods to deal with problem of poor power quality in distribution system. These methods are expensive and time-consuming. Installing the compensation equipment in the immediate vicinity is a straightforward and cost-effective way of dealing such problem [4].

An equally rapid compensating device is required to remedy and prevent the spreading of the power quality problem caused by EAF. Currently, the most widely used method for flicker compensation is the connection of shunt static VAR compensators based on thyristor-controlled reactors (TCR's). A TCR consists of a reactance connected in series with a pair of thyristors with a fixed value parallel-connected capacitor [3]. These methods, used with conjunction with fixed passive filters, have been successful in correcting the power factor and compensating the harmonics.

Even though these methods have success in solving the flicker problem by reactive power compensation, they are unable to supply any portion of the fluctuating real power drawn by the furnace. Development of high power electronics offers Flexible AC Transmission system (FACTS) several significant advantages, including the ability of passing real power between ac and dc terminals [5].

Integrating an energy storage system (ESS), such as battery energy storage system (BESS) or superconducting magnetic energy storage (SMES), into a FACTS device can lead to improved controller flexibility by providing dynamic decentralized active power capabilities. Combined FACTS/ESS not only can improve power flow control, oscillation damping, and voltage control, but also improve the power quality of the transmission and distribution systems, including mitigation of the voltage flickers caused by EAF [6].

There are controversial arguments about the effectiveness of active power compensation to solve voltage flicker problems. The reasons given are that the active injection is not effective given that most systems have an X/R ratio over 10 by looking at the transformers and transmission lines. Our study is able to resolve this issue and clearly show that the active power injection is also useful to solve voltage problems. The key here is the calculation of X/R ratio which should be the Thevenin impedance of the system seen at the point of common coupling (PCC). The system X/R ratio turns out to be much lower than 10, for example, $X / R \approx 3$ in our study system.

In this paper, the authors studied the voltage flicker problem caused by EAF in a 25 bus sample power system. The effect of the random active power drawn by EAF was discussed in detail in relation to the role of X/R ratio. Using the models in PSS/E, the authors studied the EAF voltage flicker mitigation by FACTS/ESS. The comparison of the mitigation effects by different FACTS/ESS has been shown. The effectiveness of FACTS with and without ESS is compared.

II. ARC FURNACE MODEL FOR PSS/E

An accurate three-phase arc furnace model is needed for

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the purpose of harmonic analysis and flicker compensation. Since the arc melting process is a dynamic stochastic process, it is difficult to make a precise deterministic model for an arc furnace load. The factors that affect the arc furnace operation are the melting or refining materials, the melting stage, the electrode position, the electrode arm control scheme, the supply system voltage and impedance [1].

Many complex methods were proposed to more precisely represent EAF characteristics and study its impacts on power systems. These include nonlinear resistance model, current source models, voltage source models, nonlinear time varying voltage source model, nonlinear time varying resistance models, frequency domain models, and power balance models, etc, [2,7,8].

PSS/E power system simulation software we chose to use for this study has the ability to deal with a large scale power system. It contains a very large power equipment model library. However, there is no EAF model in it. The authors created a practical arc furnace model to study the voltage flicker problem caused by EAF. The EAF model contains a resistor and a reactor in a random operation mode to display the dynamic characteristics of EAF. Because the focus here is to study the voltage flicker problem solutions by FACTS/ESS, a simple arc model will serve the purpose as long as the worst case voltage fluctuation frequency and magnitude are reflected in the model. Our arc model can generate a variation of voltage at about 0.3 ~ 1% at a frequency around 5Hz [2,3]. Harmonic problem is not considered.

The general scheme of EAF and FACTS/ESS is shown in Fig.1. In this research, the EAF is about 40MVA containing 34MW active power and 25MVAR reactive power at the normal bus voltage.

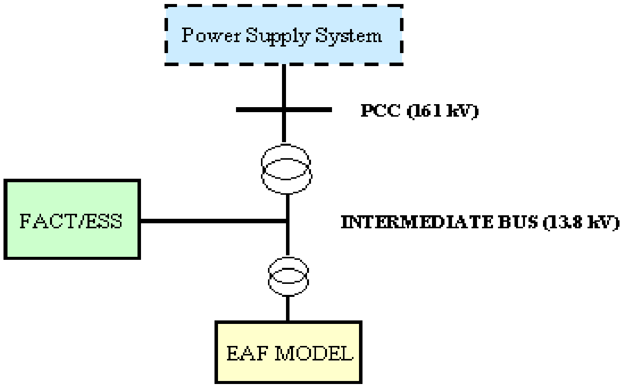

Fig.1. The general scheme of EAF and FACTS/ESS.

Fig.2 is the 25 buses sample system. The scheme of EAF and FACTS/ESS has the same configuration as shown in Fig.1.

In Fig.2, bus 153 (161kV) is the PCC bus. The EAF and the FACTS/ESS are connected to bus 1531 (13.8kV) which is referred to as the EAF bus in this paper. EAF is characterized by rapid changes in absorbing power that occur especially in the initial stage of melting, during which the critical condition of the emerging arc may become a short circuit. Fig.3 shows the characteristic of rapid active and reactive power drawn by EAF. Of course the actual real and reactive power drawn by the EAF does not always change as rapidly as shown in Fig.3. The worst situation for FACTS/ESS to handle is shown in Fig.3 . This situation will present the maximum challenge for the compensation equipments. Fig.4 shows the voltage flicker on the PCC bus and EAF bus. The voltage dip is about 1% at the frequency around 5 Hz.

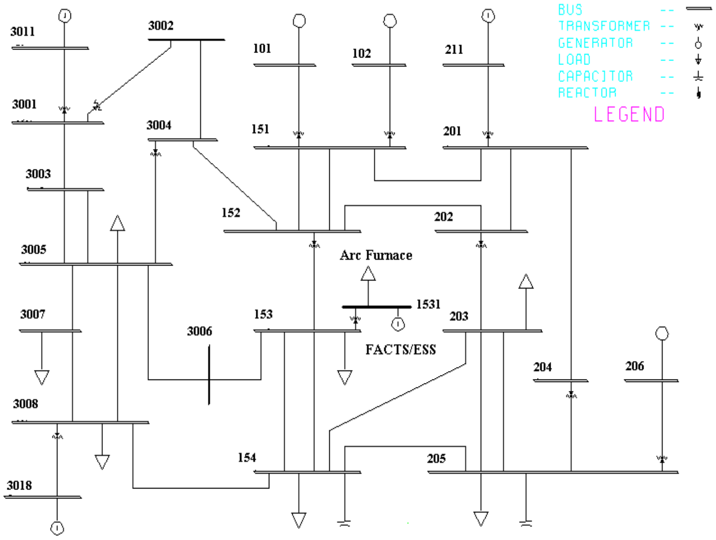

Fig.2. One-line diagram of the research system.

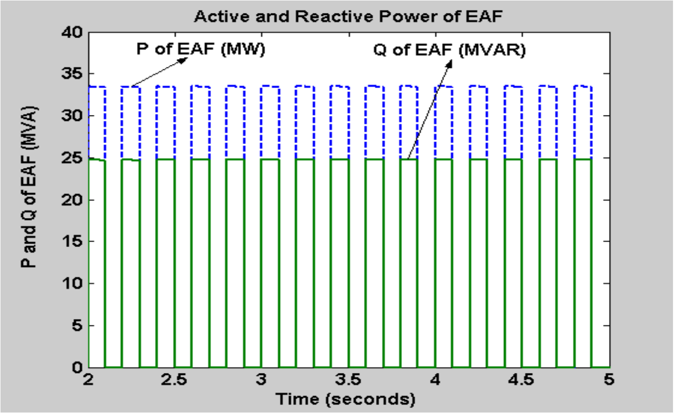

Fig.3. The rapid change of power drawn by EAF.

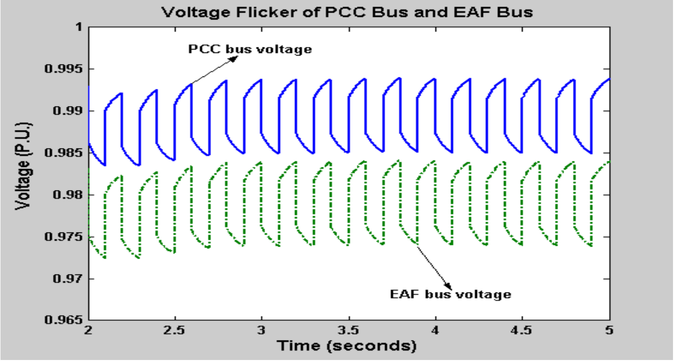

Fig.4. Voltage flickers on PCC bus and EAF terminal bus.

III. Flicker Mitigation By FACTS/ESS

The FACTS/ESS controllers are power electronic based devices that can inject both real and reactive power to not only enhance transmission system performance but also to solve power quality problems. FACTS controllers can be connected to the system in series, in parallel or in combination and they can utilize or redirect the available power and energy from the ac system. Without energy storage, they are limited in the degree of freedom in which they can help the power grid. In this study, two of the available energy storage technologies, battery energy storage system (BESS) and superconducting magnetic energy storage (SMES), are added to a STATCOM to improve the control actions of FACTS. Fig.5 shows the general configuration of FACTS/ESS. Fig.6 is an example of the FACTS with the super conducting magnetic energy storage device (SMES) [9].

In this study, we choose the capacity of the FACTS/ESS to meet the demand of the EAF. As the EAF capacity in the study is 40MVA, the FACTS/ESS in the simulation is 50MVA with 20MW active capacity. In this study, we looked at the EAF- caused voltage flicker mitigation by STATCOM, FACTS/BESS and FACTS/SMES. The following are some simulation results to show the effects of the above controllers.

As we know, the energy stored in ESS is limited. If the FACTS/ESS does not replenish its store of active power from the system, the ESS will run out of its active energy (active power) and will behave like a STATCOM, which can only output reactive power. However, the STATCOM can improve the EAF bus voltage as well as the FACTS/ESS does, because the reactive power control scheme of FACTS/ESS is local bus (EAF bus) voltage control. But it cannot improve the voltage of PCC bus as well as the FACTS/ESS because of the lack of active power output. The reasons are discussed in the X/R ratio discussion section. Fig.7 to Fig.9 show the operation mode of the FACTS/SMES when it does not absorb active power from system.

In Fig.7, the energy stored in SMES is depleted within 0.5 seconds if active power is not absorbed from the system. Once this occurs, the reactive power output of FACTS/SMES will rise to control the EAF bus voltage to the desired level. At this time, the FACTS/SMES acts like a STATCOM.

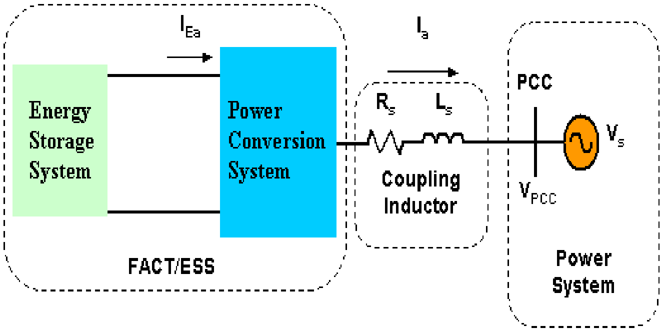

Fig.5. Typical configuration of FACTS/ESS.

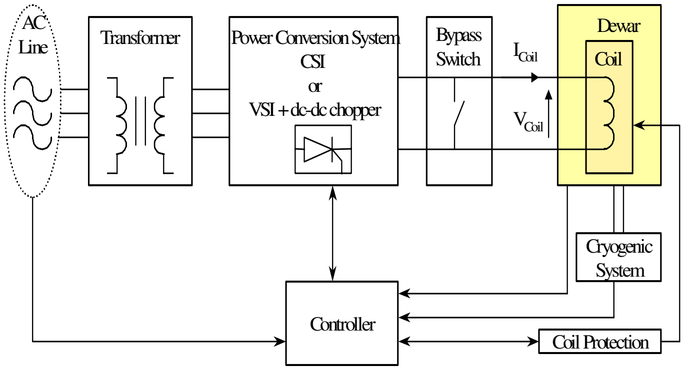

Fig.6. The sample configuration of FACTS/SMES.

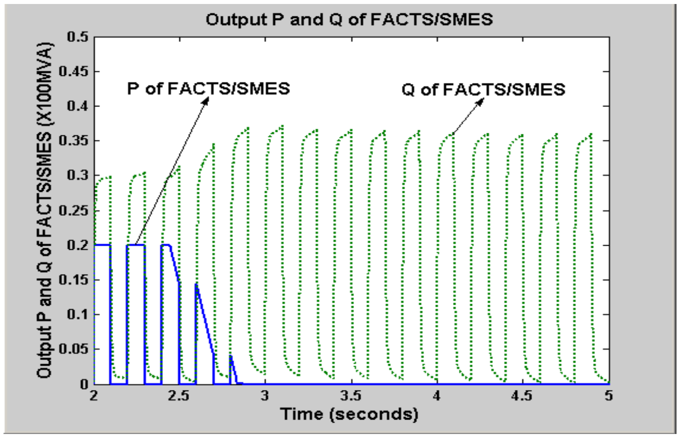

Fig.7. P and Q of FACTS/SMES (Without P absorption).

As the active power output of FACTS/SMES decreases and diminishes, the system will transfer more active power and reactive power to the EAF, which is shown in Fig.8. What is interesting is that the transferring reactive power improves as well. That is because of the voltage drop on the R_n which will be explained in the X/R ration discussion section. In Fig.9, we can see that even though the EAF bus voltage can be improved to the desired level, the PCC bus voltage cannot be improved to the original reference value when FACTS/SMES only outputs reactive power.

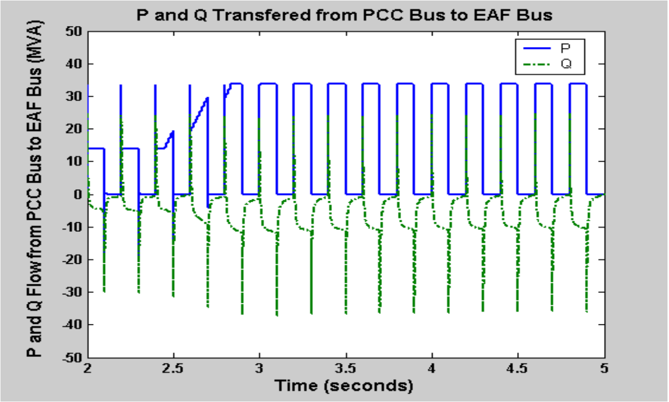

Fig.8. P and Q transferred from PCC bus to EAF bus (FACTS/SMES has no active power absorption).

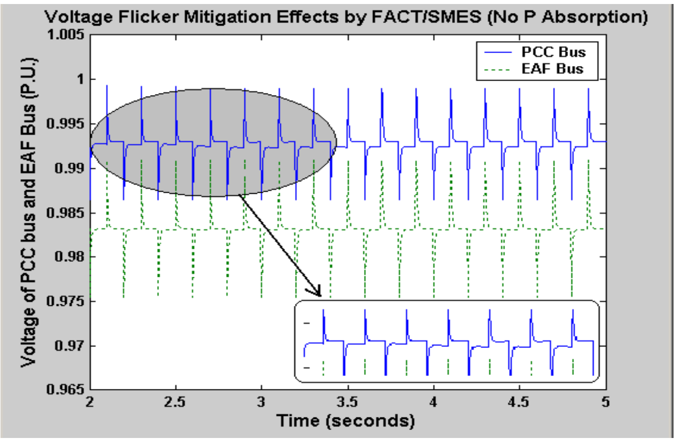

Fig.9. Voltage of PCC bus and EAF bus (FACTS/SMES has no active power absorption).

In this study, we control the FACTS/ESS to absorb active power during the period when EAF is taking less active power from the system. In this operation mode, the FACTS/ESS can work in a continuous mode to supply active power during the whole EAF operation period. Of course, the absorption of active power of EAF can cause voltage drop at the PCC and EAF bus, but these voltage drops are relatively small. Again, the X/R ratio plays an important role.

In this continuous operation mode, the reactive power output of FACTS/ESS will not be zero even when EAF is out, as it attempts to compensate the voltage drop caused by the active power draw by ESS as shown in Fig.10.

In practice, the active and reactive power change of EAF is not as steep as shown in this paper. EAF have a period of rising time, which means the slope of the active and reactive power must not be as sharp as shown in the Fig.3. The spikes in Fig.9 through Fig.17 will not be as high.

In Fig.11, the effects of voltage flicker mitigation at the PCC bus and EAF bus are the same. In Fig.12 and Fig.13, we can see that the mitigation effects of BESS and SMES are the same which is better than that of STATCOM. But all of these (STATCOM, BESS and SMES) mitigate voltage flickers caused by EAF effectively. To the EAF bus, the three solutions are equitable.

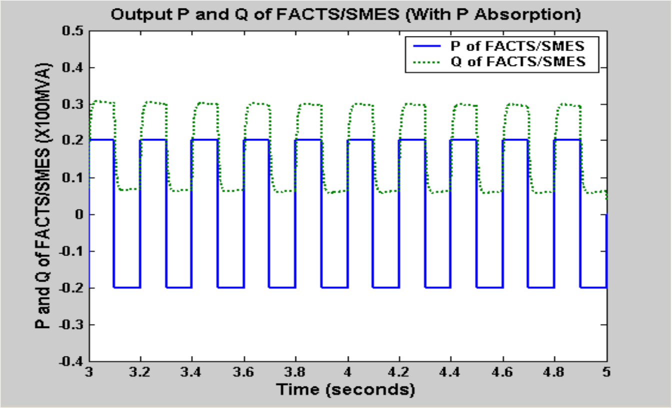

Fig.10. P and Q of FACTS/SMES (With Active Power Absorption).

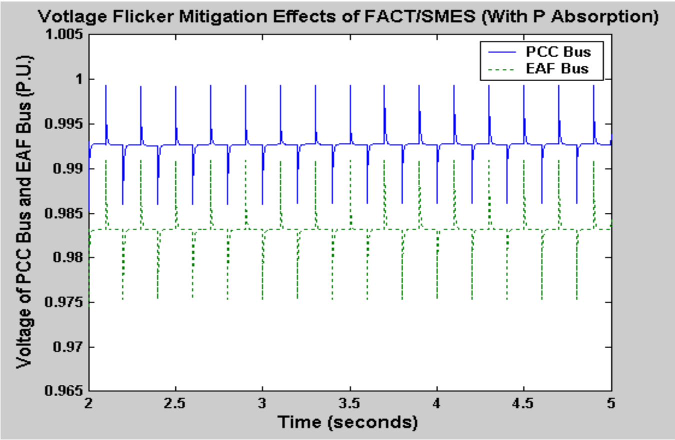

Fig.11. Voltage of PCC bus and EAF bus (With Active Power Absorption).

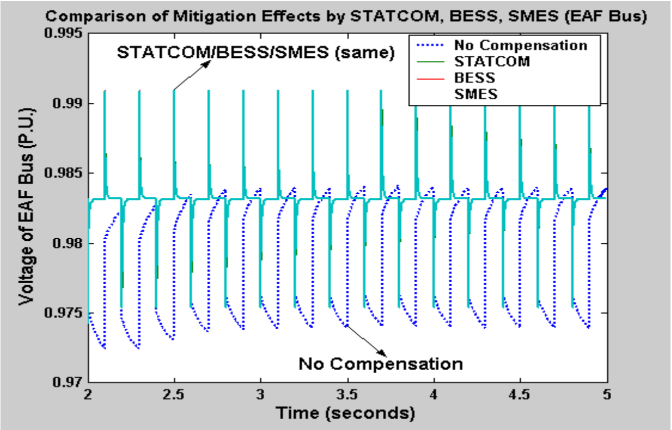

Fig.12 Comparison of EAF bus voltage compensated by STATCOM, SMES and BESS

In Fig.13, we can see that the PCC bus voltage is higher when compensated by STATCOM than by FACTS/ESS. The reason is that the FACTS/ESS absorbing active power causes a voltage drop on PCC bus. Because the control scheme of the FACTS/ESS is to control the EAF bus voltage to the desired level, the PCC bus voltage cannot be improved as much as the EAF bus. This will be explained in Section IV.

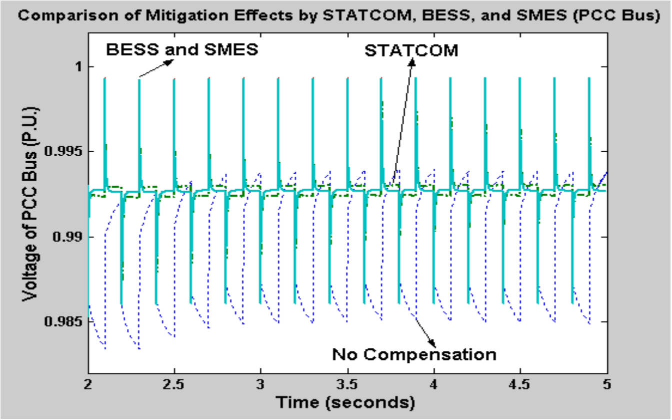

Fig.13. Comparison of PCC bus voltage compensated by STATCOM, SMES and BESS.

IV. X/R RATIO DISCUSSION

As mentioned above, the voltage effect of active power drawn by EAF is reflected by the real part of system impedance (Thevenin Impedance) R_n. A very common mistake is to assume that in the power system, the X/R ratio is large enough to omit the voltage drop caused by the active power of EAF. An incorrect approach to calculating X/R ratio is by considering only the upper transformer or branch and one will certainly arrive at an X/R over 10. The correct approach should be looking at all the parameters including the load. In other words, the R and X are not proportional to the impedance of the upper transformers and lines, they should be the Thevenin impedance seen from the PCC bus of the entire system.

The following example will show how we can roughly estimate the value of X/R ratio at PCC. At the PCC bus, the whole power system can be seen as a power source connected with an active load and a reactive load as shown in Fig.14 (a). The Thevenin Equivalent circuit is shown in Fig.14 (c).

In the research system, according to the simulation results, the total power $P_{L\Sigma}$ is 3200MW and $Q_{L\Sigma}$ is 1950MVAR. V_{LLbase} is 21.6kV and S_{base} is 100MVA. The impedance of one generator is $Z_{s1} = 0.01+j0.3$ pu. Since

$$Z_{base} = \frac{V_{LLbase}^2}{S_{base}} = 4.666\ \Omega \tag{1}$$

then Z_{s1} is 0.04666+j1.3998Ω. There are 6 generators in the system. For simplicity, assume they are connected in parallel to supply power to the load shown in Fig.14 (a). Then the whole system impedance Z_s is 1/6 of that of one generator, then, Z_s =0.0079+j0.2333Ω. The estimated total load impedance is

$$\begin{cases} R_L = \dfrac{V_{LLbase}^2}{P_L} = 0.1458\ \Omega \\ X_L = \dfrac{V_{LLbase}^2}{Q_L} = 0.2393\ \Omega \end{cases} \tag{2}$$

As shown in Fig.14(b-c), we can compute the $R_n+jX_n=0.0589+j0.0716\Omega$, and $X_n/R_n=1.22$. In this example, the values of X_n and R_n are not precise but enough to demonstrate that the system X/R ratio is affected significantly by the load. After adding impedances of adjacent transformer and line, X/R is still not large enough to omit R at EAF bus.

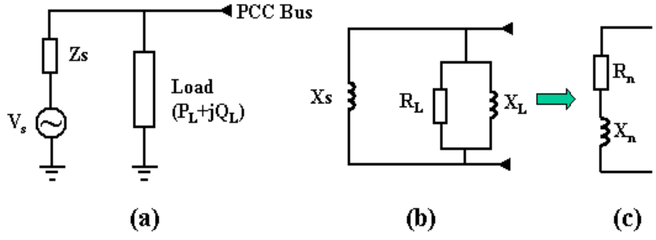

Fig.14 Thevenin equivalent circuit of the whole system seen at PCC bus.

In our case, the system Thevenin Impedance (R_n+jX_n) seen at PCC bus is 0.00782 +j0.02389 pu, which was calculated precisely in PSS/E. The X_n/R_n ratio is about 3. In this case, the active load can cause obvious voltage drop as seen in the above simulation results. In other words, the active power of FACTS/ESS can play an obvious role in voltage compensation as shown in the above study results.

A detailed analysis of the X/R ratio on voltage impact is given here. The equivalent impedance (X_n,R_n) shown in Fig.15 is the Thevenin equivalent of the whole sample power system looking at PCC bus. U_0 is the source voltage of the Thevenin equivalent circuit. The X/R ratio is not that of the upper transmission line or upper transformer but that of the Thevenin equivalent impedance (X_n,R_n).

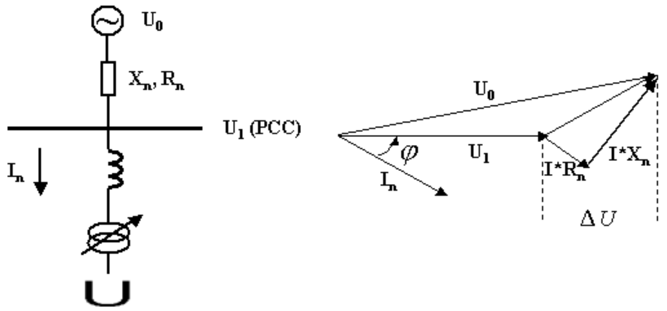

Fig.15 Discussion of X/R ratio.

In Fig.15, the voltage drop of EAF is ΔU, which contains a real part ΔU_p and a reactive part ΔU_q shown in the following equations:

$$\Delta U = \frac{\sqrt{3}}{3} I_n * X_n \left(\sin\varphi + \frac{R_n}{X_n} * \cos\varphi\right) \tag{3}$$

$$\Delta U_p = \frac{\sqrt{3}}{3} I_{np} * R_n \tag{4}$$

$$\Delta U_q = \frac{\sqrt{3}}{3} I_{nq} * X_n \tag{5}$$

I_{np} and I_{nq} are given as:

$$I_{np} = I_n \cos\varphi \tag{6}$$

$$I_{nq} = I_n \sin\varphi$$

(7)

In this case, the active power and reactive power of EAF is 34MW and 25MVAR respectively. Fig.16 shows the voltage drop by 34MW active load, 25MVAR reactive load and 40MVA (34MW+j25MVAR) combined load. The calculated ratio of voltage drop caused by 34MW active load and 25MVAR reactive load is about 0.445, which is given by equation 8.

$$\frac{\Delta U_p}{\Delta U_q} = \frac{I_{np}}{I_{nq}} * \frac{R_n}{X_n} = \frac{R_n}{X_n} * \tan^{-1}\varphi = 0.445 \tag{8}$$

In which $\cos\varphi = 0.8$ and $R_n = 0.3273 X_n$.

The simulation results agree well with the X/R ratio analysis. It is clear that we need to pay attention to the role of active power compensation when we study the voltage flicker caused by EAF. FACTS with ESS could be a better device to mitigate the voltage flickers caused by EAF.

Fig.17 and Fig.18 show the comparison of voltage flicker mitigation effect by FACTS/BESS with and without active power output. We can see that for the EAF bus, the effects look the same because of the control scheme of the

FACTS/ESS. But for the PCC bus, the effect with active power output of FACTS/BESS is better than that without active power output. It is important to note that the reactive power output of the FACTS/BESS rises when it has exhausted its active power reserve, which is shown in Fig.19. The reason is that it takes more reactive power to improve the voltage of EAF to the same level when no active power is available. In Fig.17, the voltage difference by the two compensation approaches is due to the fact that the 20MW active power absorbing by ESS causes the voltage drop on the PCC bus.

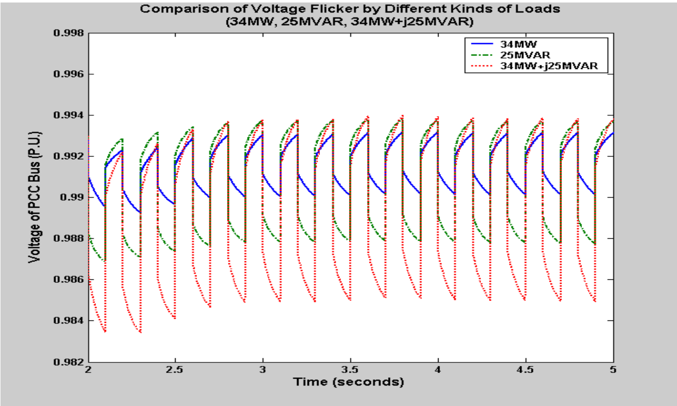

Fig.16 Comparison of voltage drops at PCC Bus with different types of load. (34MW, 25MVAR and 34MW+j25MVAR)

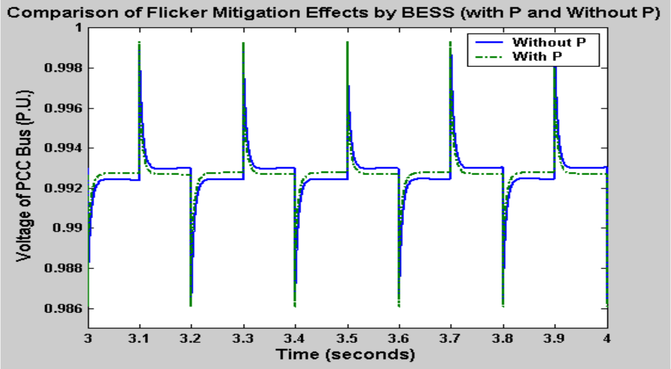

Fig.17 Comparison of PCC bus mitigation effect by FACTS/BESS (With and Without P)

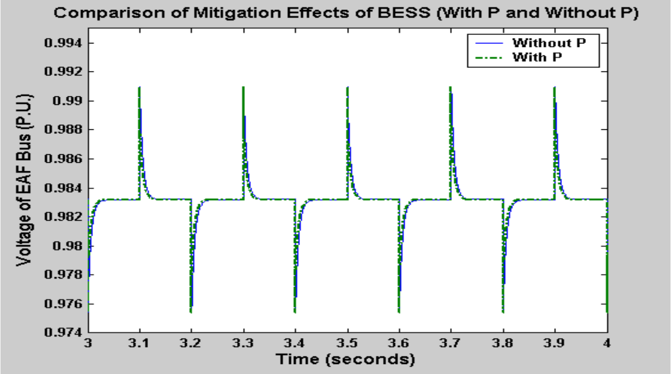

Fig.18. Comparison of EAF bus mitigation effect by FACTS/BESS (Without and With P)

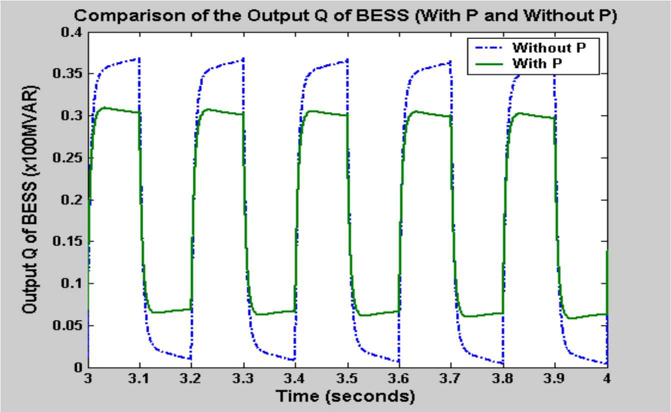

Fig.19. Comparison of reactive power output of BESS (Without and With Active Power Capability)

V. CONCLUSION

The operation of electric arc furnace can cause power quality problems, especially as voltage flickers, to the power supply system to which it is connected. Nowadays, most utilities and power customers are facing the need to solve the power quality problem created by EAF. Some may falsely believe it is only the reactive power demand of the EAF that causes the voltage flicker. This mistake stems from the assumption the X/R ratio is determined mainly by the up-stream transformer or transmission line, which is typically larger than 10. Indeed, for such a high X/R ratio, active power can play a minor role in boosting the bus voltage. The authors have shown the discussion of X/R ratio should be from the point of view of the whole system, which means R and X are not just the impedance of the upper transformer or line, they should be the Thevenin impedance seen from the PCC bus of the whole system. In our study, the active power drawn by EAF also contributes obviously to the voltage flicker. The reason is that actual system X/R ratio is within a range (X/R≈3 in our sample system) that makes the active power load influencing the voltage drop of the PCC bus. This also proves the need for active power, not only reactive power, to mitigate this kind of voltage problems.

The FACTS with ESS has advantages over FACTS alone by supporting the active and reactive power at the same time. In this paper, the authors analyzed the effects of the FACTS/ESS in mitigation of voltage flickers caused by EAF. A practical EAF model is created to simulate the change of active and reactive powers drawn by an EAF. Different operation modes of the FACTS/ESS have been discussed. The simulation results were presented. The study showed that FACTS with ESS can be more effective than using the FACTS devices alone.

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VII. BIOGRAPHIES

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