Transient Performance of Vacuum-Switched Static VAR Compensators Optimised for Large Inductive Loads

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Abstract - **ASDEX Upgrade (AUG), an experimental tokamak device for nuclear fusion research, requires an electrical power up to a few hundred MVA for a time period of 10 – 20 s. Static converters powered by flywheel generators are used to feed the magnet coils of AUG. Engineering activities devoted to optimising the existing power supply by static var compensators (SVC) are under way to satisfy future power demands. Sudden load changes can occur in the flywheel generator networks and the busbar voltages can be extremely distorted while thyristor converters are operated at high current levels during an AUG load pulse. A major concern under these conditions is to avoid a resonant excitation of SVC modules. The paper presents the design criteria for the installed SVC modules, measurement results under normal and fault conditions (switching, resonant excitation) and design improvements derived from numerical simulations. These will provide harmonic filtering and allow to economically compensate large amounts of reactive power (120 MVAr) by vacuum-switched SVC devices.**

Keywords: SVC, reactive power, harmonics, resonances, asymmetrical load, isolated network, transient analysis

I. INTRODUCTION

During the next few years AUG will strengthen its efforts concerning investigations of advanced tokamak scenarios. To fully exploit these operating modes, a plasma flattop time of at least 2-3 skin times, i.e., 10 seconds will be necessary [1]. AUG long pulse operation of 10 s will be achieved by a reduction of the plasma current to a value of 1 MA. In contrast to the short pulse operation (e.g. 4-5 s at 1.4 MA), it is required for the 1 MA long pulse operation to fully exploit the flywheel energy of the generators EZ3 and EZ4 which feed different networks and have rather different properties:

- EZ3 has a flywheel energy of 500 MJ and a short pulse apparent power of 144 MVA which drops below 100 MVA after an effective supply time of 8 s.
- EZ4 has a flywheel energy of 650 MJ and a short pulse apparent power of 260 MVA

In relation to the generator EZ4, the flywheel generator EZ3 provides an up to 60 % smaller ratio of apparent power to flywheel energy. Hence, reduction of part of the apparent power in compensating reactive power by static compensators is required for this generator in order to take full advantage of the available flywheel energy. Satisfactory conditions for long pulse operation can be achieved with a reactive power compensation plant consisting of four 30 MVAr modules (referred to a frequency of 100 Hz) [1] as shown in Figure 1.

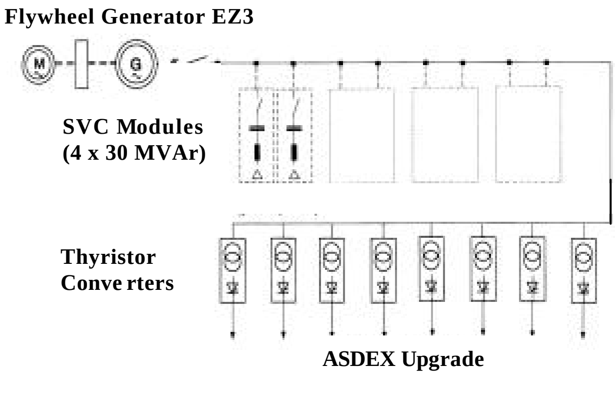


Fig. 1. Arrangement of the SVC modules in the 10.5 kV flywheel generator network

The compensation is provided by tuned capacitor banks being energised by line synchronised vacuum breakers. That solution is far less expensive than thyristor controlled compensation but requires an accurate tuning with regard to the generator and load characteristics in order to keep transient phenomena at an acceptable level. Analytical and numerical investigations were performed to investigate the operational boundary conditions and to derive a design with acceptable voltage and current surges under normal and fault conditions [2].

In 1998, a 30 MVAr prototype unit consisting of two vacuum-switched 15 MVAr modules (see Fig. 2) was commissioned.

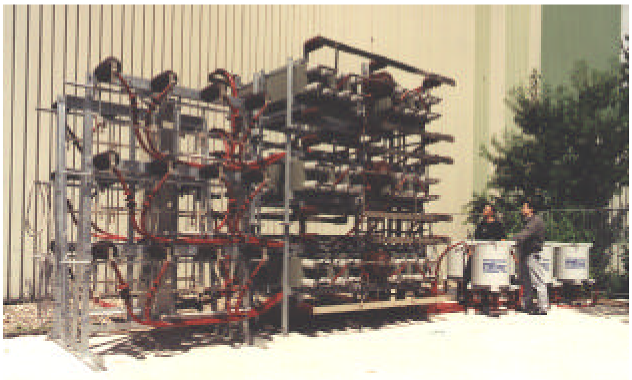


Fig. 2. Outdoor installation of prototype SVC unit

The three-phase arrangement of that unit is shown in Fig. 3

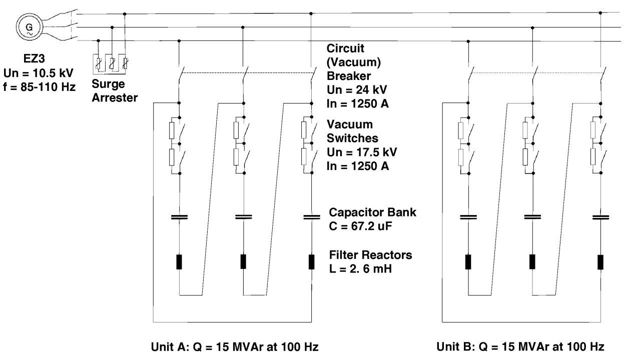


Fig. 3. Three-phase arrangement of 30 MVAr unit

Since then, more than 1500 load pulses with static var compensation have been performed. Based on the experience with the installed unit an extension of the SVC facility to 120 MVAr is under construction. The total system will consist of eight vacuum-switched 15 MVAr modules. The number of modules per load pulse as well as the optimum time for switching each module is determined by the SVC control system and will depend on a measurement of the reactive power supplied by the flywheel generator power supply.

II. SVC DESIGN AND OPERATIONAL EXPERIENCE

The large inductive voltage components required during plasma ignition and ramp-up of the poloidal field (PF) magnet coils lead to a large reactive load component for the generator. The reactive power reaches its maximum at the flat top of the plasma current (t > 1.2 s in Fig. 4), where the high ramp-up voltage level of the coil circuits is no longer required and the coil currents have reached their maximum values. The characteristics of the reactive power during an AUG load pulse was the determining factor for the decision to compensate reactive power by switchable capacitor banks. The vacuum switches are equipped with a synchroniser gear specially developed for distorted supply voltages. That way electrical transients can be kept at acceptable levels, see Fig. 4, despite of the problems to be faced in the variable frequency network of flywheel generator EZ3. During an AUG load pulse the frequency in the EZ3 network may decrease from 110 Hz to 85 Hz and sudden load changes can occur. Hence, the period length varies between 9 and 11.7 ms. In order to achieve a switch-on of the SVC units synchronised with the voltage-zero crossings of the three phases it must be considered that even fast vacuum breakers have closing and opening delay times of about 33 ms respectively 17 ms. The thyristor rectifier units cause a considerable amount of harmonics which makes the recognition of the natural zero-crossing difficult. In addition the closing and opening times of suitable vacuum breakers have a jitter. Even small jitters (0.5 ms in the best case) cause electrical transients at period lengths of typically 10 ms. Despite of these problems it can be summarised from the load pulses performed so far (> 1500) that no problems related to the synchronised switching of the installed SVC modules have occurred, i. e. the transient phenomena at switching of the modules are negligible. A typical measurement result is shown in Fig. 4.

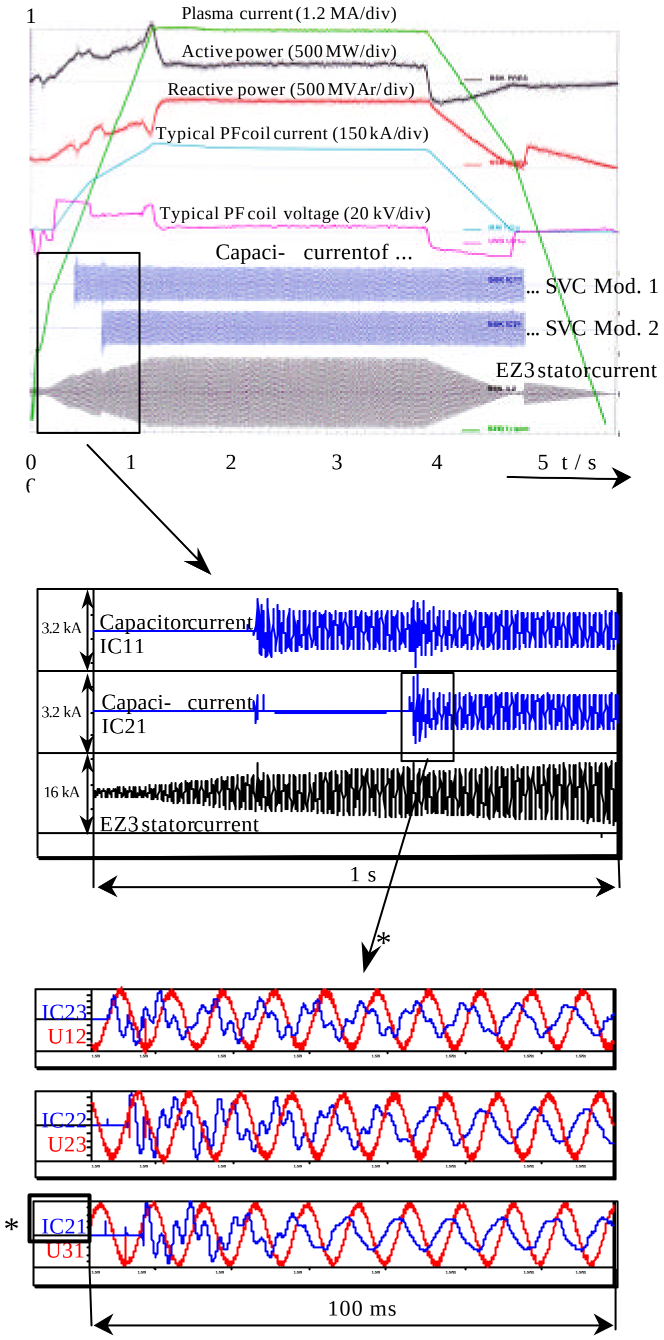


Fig. 4. AUG load pulse (#11224, 1.2 MA) with reactive power compensation (2 x 15 MVAr)

III. ANALYSIS OF FAULT CONDITIONS

A. *Unsynchronised switching*

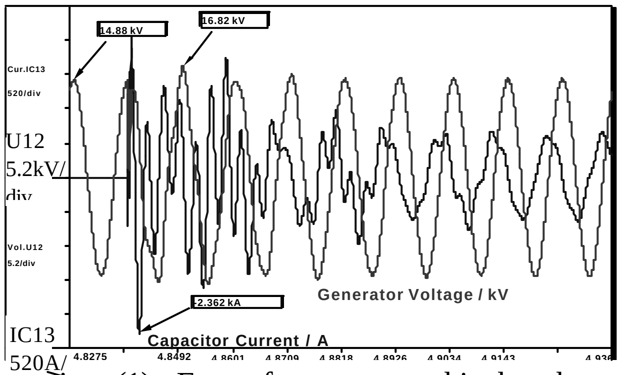
For safety reasons all components have been designed for unsynchronised switching. For a rough calculation of the maximum switching surge Δu at the generator busbars the following formula can be derived [2]:

$$\Delta u = \frac{\Delta U_N}{U_{N0}} = \frac{1}{1+k} \cdot \left(1 - \frac{U_{C0}}{U_{N0}}\right) = 0.208 \cdot \left(1 - \frac{U_{C0}}{U_{N0}}\right) \quad (1)$$

($k = 3.8$)

U_N: Nominal busbar voltage; U_{N0}: Synchronous internal voltage at $t = t_0$ (t_0: switching instant), U_{c0}: Capacitor voltage at $t = t_0$

In normal operating mode the individual SVC modules are switched on and off automatically but only once during each load pulse (U_{C0} = $-U_N$ after each load pulse). To limit the maximum overvoltage at unsynchronised switching the next load pulse is inhibited until $U_{C0} \approx 0$. The number of units/modules and optimum time for switching each module is determined by the SVC control system and depends on a measurement of the reactive power supplied by generator EZ3. The worst case scenario is switching on a SVC module at maximum phase-to-phase voltage. In that case the maximum transient voltage at the generator busbars is only about 20 % higher than the nominal voltage - see



equation (1). For safety reasons this has been tested during commissioning: The measured busbar voltage and capacitor current is displayed in Fig. 5.

Fig. 5. Measured capacitor current and busbar voltage at unsynchronised switching-on of SVC module (worst case)

Whereas no major overvoltages can occur at the generator busbars due to unsynchronised switching, the capacitor voltage can rise up to 30 kV in that case (Fig. 6) which is considered in the design values of all components.

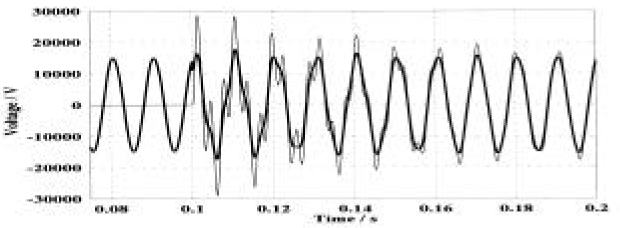


Fig. 6. Simulated busbar and capacitor voltage at unsynchronised switching-on of SVC module

B. Excitation of resonances

More than 1000 load pulses with reactive power compensation were performed without any problems. During an experimental campaign which required high rotational speeds of flywheel generator EZ3 (corresponding to network frequencies > 105 Hz), resonances were observed in SVC modules. The resonances occurred during the flat-top phase of the plasma current (Fig. 4) where – under normal conditions – the SVC modules are in the steady state. As shown in Fig. 7 the module currents rise up to values of about 2.4 kA (almost four times the nominal value) before the SVC modules are switched off by the overcurrent-time protection.

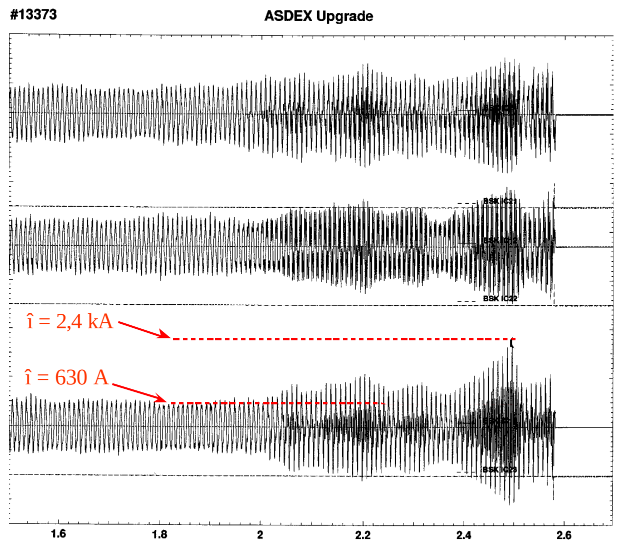
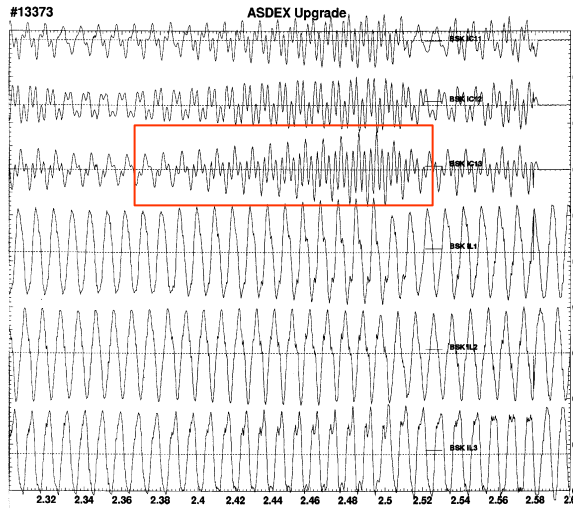
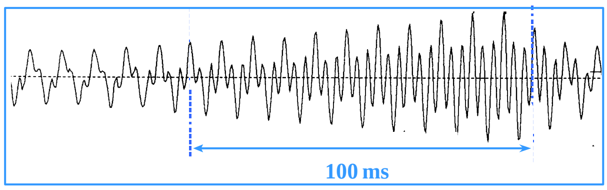


Fig. 7. Resonant excitation of SVC module (AUG # 13373): Measured capacitor currents (in the three phases of one SVC module)



Besides the fact that overvoltages occur within the SVC modules during resonant excitation (as outlined in the section *Unsynchronised switching*) the resonant currents also cause an asymmetrical load component for the synchronous generator which can be seen in the phase currents of EZ3 displayed in Fig. 8.

Fig. 8. Resonant excitation of SVC module (AUG # 13373): Measured capacitor currents and corresponding stator currents of generator EZ3



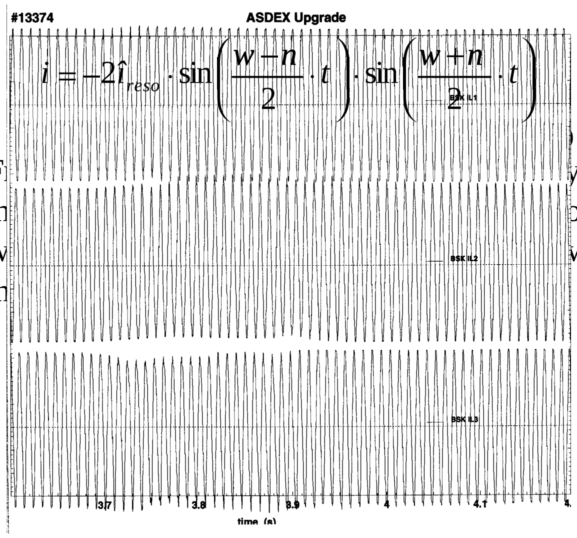
(IC: 30 kA/div, IL: 100 kA/div)

To find the cause of resonances the measured curves were investigated in more detail. Fig. 9 shows a zoom of Fig. 8 which allows to analyse the frequencies of the resonant currents in the time domain.

Fig. 9. Resonant excitation of SVC module (AUG # 13373): Detail of Fig. 8.

The beat curve shown in Fig. 9 consists of two frequencies: 11 Hz and 329 Hz which can be explained analytically from the differential equations of an RLC equivalent circuit being excited by an alternating voltage with frequency ω. In the case that ω is close to the resonant frequency ν of the RLC circuit (ω ≈ ν), the following formula for the current i can be derived [3]:

$$i = -2\hat{i}_{reso} \cdot \sin\left(\frac{w-n}{2}\cdot t\right)\cdot \sin\left(\frac{w+n}{2}\cdot t\right)$$



IL1

IL2

IL3

0

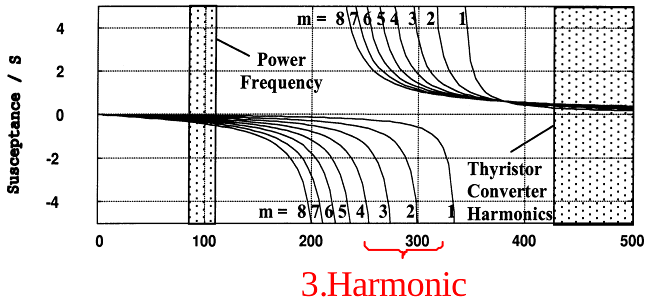
Fig. 10. Asymmetrical load of generator EZ3 (fault condition): Stator currents during load pulse without SVC (AUG #13374), IL:60kA/div

Such stator currents have rarely been observed during operation of AUG. It is assumed that they are caused by remaining inaccuracies in the gate control of one of the high current converters. The curves displayed in Figs. 7-9 were measured at a system frequency of 106 Hz, i. e. the third harmonic of that system frequency is ω_3 = 318 Hz. The per-unit natural frequencies n of the SVC system can be determined by [2]:

$$\left(\frac{\nu_c}{\nu_0}\right)^2 = \frac{X_C}{3X_d''(m+k)} \quad (3)$$

X_c : reactance of capacitor C; X_L: reactance of SVC inductor, X_d'': subtransient reactance of EZ3; k = X_L / 3 X_d''; m: number of RPC units

During AUG shot # 13373 only one SVC module was connected, for which a resonant frequency ν = 340 Hz can be calculated by means of equation (3). I. e. the following parameters of the sine functions in equation (2) can be derived



$$\frac{\nu_3 - n}{2} \approx 11\,Hz \qquad \frac{\nu_3 + n}{2} \approx 329\,Hz$$

So far the cause for the rare occurence of asymmetrical load components could not be identified yet. Therefore, it must be assumed that the occurrence of third harmonics in the IPP system cannot be excluded for future load pulses, so that consequences for the design of the SVC system must be drawn. The points of resonance of the system which can be calculated by equation (3) are displayed in Fig. 11.

Figure 11: Susceptance functions of m = 1...8 RPC modules in the EZ3 network

IV. SVC DESIGN IMPROVEMENTS

It cannot be excluded that third harmonics will occur in the EZ3 network. Because of the variable frequency, the third harmonic can cause a resonant excitation of SVC modules in the whole frequency range (85-110 Hz), depending on the number of modules connected during the load pulse (see Fig. 11). Under these conditions the most promising design improvement was to install additional resistors which will be connected in parallel to the SVC inductor (Fig. 12). They have a resistance value of 70 Ω, and provi[illegible] the 3rd harmonic.

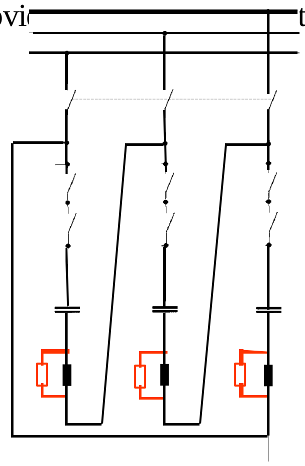


Fig. 12. SVC module: Extension by damping resistances tuned to the 3rd harmonic

The effect of the damping resistances was numerically investigated. Results from simulations using the Simplorer code [4] are shown in Fig. 13. The upper curve was calculated assuming that one SVC module without additional damping resistances is excited to resonances due to an asymmetrical component of the load current of EZ3, similar to the fault in Fig. 9. The lower simulation result was achieved using the same input parameters, but the SVC simulation model was additionally equipped with 70 Ω resistances, as shown in Fig. 12.

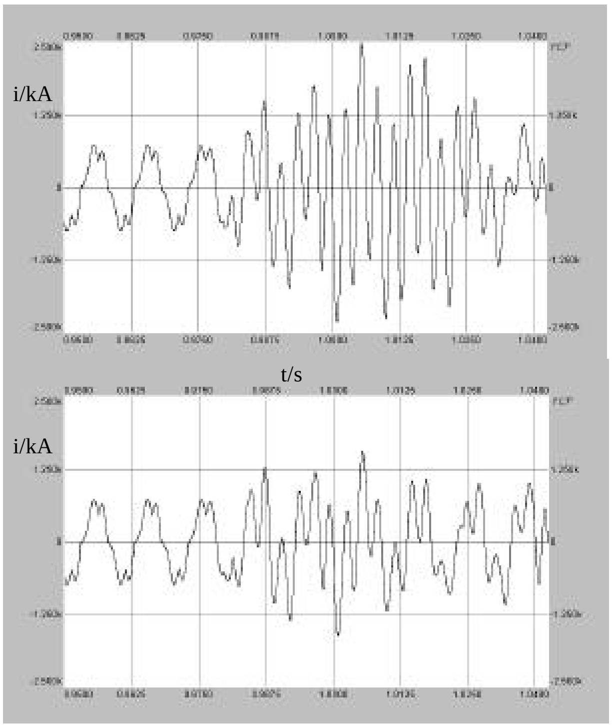


Fig. 13. Simulated capacitor current at resonant excitation of one SVC module with / without (lower / upper curve) damping resistances

The simulation results show that after installation of the damping resistances the SVC modules will be sufficiently invariant against resonant excitation caused by minor asymmetrical faults as they can occur in the flywheel generator network during high power pulses.

V. CONCLUSION

Based on the experience gained with a 30 MVAr reactive power compensation unit with two vacuum-switched SVC modules (prototype unit) an extension of the SVC system to 120 MVAr is under construction.

More than 1500 load pulses were performed and the transient performance of the SVC prototype unit was very satisfactory. In rare cases resonances in SVC modules could be observed which can be explained by the rough conditions in the EZ3 flywheel generator system during high power pulses. Therefore, all SVC modules will be equipped with additional damping resistors which will ensure a proper damping behaviour in case of resonance in the range of the 3rd harmonic. It is expected that this design change will lead to a high availability of the SVC system despite of the presented network problems.

From the experience gained so far it can be concluded that SVC by vacuum-switched devices is a reliable and economic way to compensate large amounts of reactive power.

VI. REFERENCES

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