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Dynamic Response of Power Conditioning Systems for Superconductive Magnetic Energy Storage

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Abstract -The dynamic response of two new power conditioning systems for Superconductive Magnetic Energy Storage (SMES) are presented. One power conditioning system is based on a hybrid current sourced inverter (CSI), the second is a combination of a dc chopper with a voltage sourced inverter (VSI). The response of both systems to a load change, a three phase fault and start-up is presented in this paper.

Keywords: SMES, Energy Storage, Power Conditioning, Hybrid CSI, Chopper, VSI.

Introduction

Two different power conditioning systems for the superconductive magnetic energy storage (SMES) system are presented in reference [1]. The first proposed system is a hybrid CSI. In this scheme, parallel CSIs allow for the distribution of the SMES current and the GTO based inverters allow the system to have independent control of the real and reactive power. In addition the hybrid scheme uses one transformer to link the two parallel converters which limits the transformer rating to the maximum delivered power level.

The second proposed system is a combined VSI-Chopper system. This system uses a DC-DC converter coupled with a VSI to solve the high converter rating problem associated with SMES applications. The VSI provides four quadrant operation with the ac system while the chopper controls the dc current and voltage levels.

The Electro Magnetic Transient Program ,(EMTP) is used for simulating the dynamic behavior of both proposed systems [2]. The events studied are changes in AC load , response to AC faults and the start-up procedure.

Figure 1 shows the general configuration of the simulated system. In both cases, a 100 MW inverter module links the SMES coil to a 110 kV AC bus. The AC system is modelled by its Thevenin equivalent with a short circuit ratio (SCR) of 4.0, where SCR is defined as the ratio of the short circuit MVA of the power system to maximum power transfer. The AC load is assumed to be of pulsating nature. The load ranges

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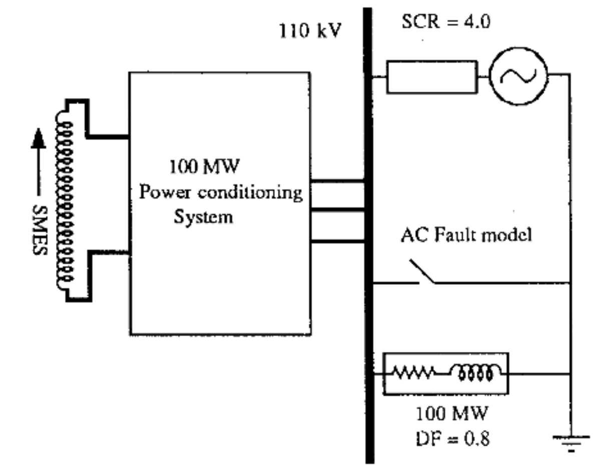


Figure 1 *General configuration of the simulated systems*

from a minimum level of 50 MW and a maximum of 100 MW. The displacement factor of the load is assumed to be 0.8 lagging at all power levels. On the DC side, the SMES coil is modelled as an inductor with zero resistance. The coil current is assumed to range from a maximum of 50 kA to a minimum of 15 kA. The coil voltage levels can be any value between 6.6 kV and - 6.6 kV.

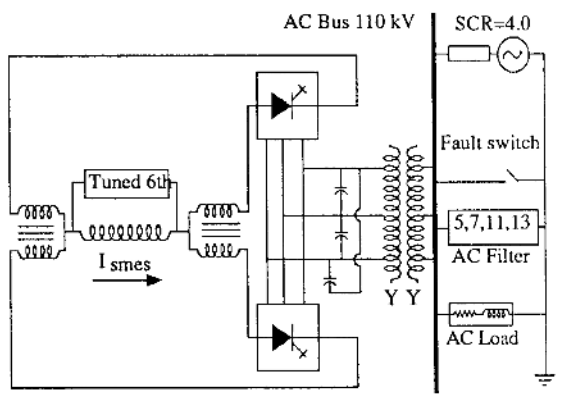


Figure 2 *Simulation model of a 100 MW hybrid CSI*

Hybrid CSI

Figure 2 shows the model for a 100 MW hybrid CSI. This converter consists of two 6-pulse, 50 MW GTO bridges connected in parallel. They used a single transform and delta connected capacitors to reduce cost. The capacitors help limit switching overvoltages and provide a commutation path for GTO turn off. Since the hybrid system is modeled as a 6-pulse system, tuned 5th, 7th, 11th and 13th AC filters are used on the AC side. On the DC side, the inverters are connected in parallel through two sets of coupled reactors to insure current sharing. A 6th harmonic filter is used to reduce the voltage distortion across the SMES coil.

Control Algorithm for the Hybrid CSI

The control algorithm for the system is assumed to be open loop for the real and reactive power (P and Q) demands of the AC system. Figure 3 shows the control block diagram of the simulated system. The inputs are the real power (P), the displacement factor of the AC load (DF), the coil current (I_{smes}) and the AC bus voltage (V). The outputs are the firing angle delays of the two inverters which are represented by $\alpha 1$ and $\alpha 2$. The L and C represent the leakage inductance of the transformer and the commutation capacitors of the hybrid converter respectively. The capacitance of the filters and the inductance of the AC system are neglected. For derivation of the equations refer to reference [1].

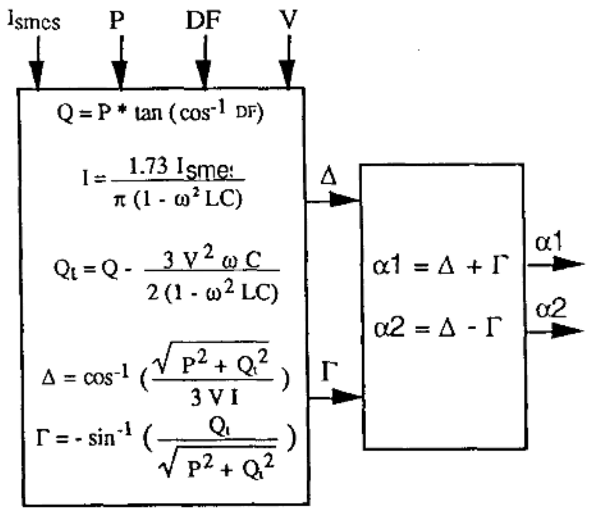


Figure 3 *The control block diagram*

In principle the firing angle delays, $\alpha 1$ and $\alpha 2$ must be referenced, or synchronized, to the AC bus voltage. In these studies, the firing signals are synchronized to the positive sequence of the fundamental component of the AC voltage to avoid harmonic problems. The synchronizing circuit calculates the Fourier coefficients corresponding to the positive sequence of each phase by integrating each over the last half cycle [2]. This positive sequence component is then used as an $\alpha = 0$ reference for calculating the correct firing time for each GTO.

Dynamic Response to AC load changes.

The most basic event is a change in the AC load demands. In this case, the real power demanded is assumed to drop from 100 MW to 50 MW and then returns to 100 MW two hundred milliseconds later while the displacement factor of the load is kept constant at 0.8. Figure 4 shows the response to the load change.

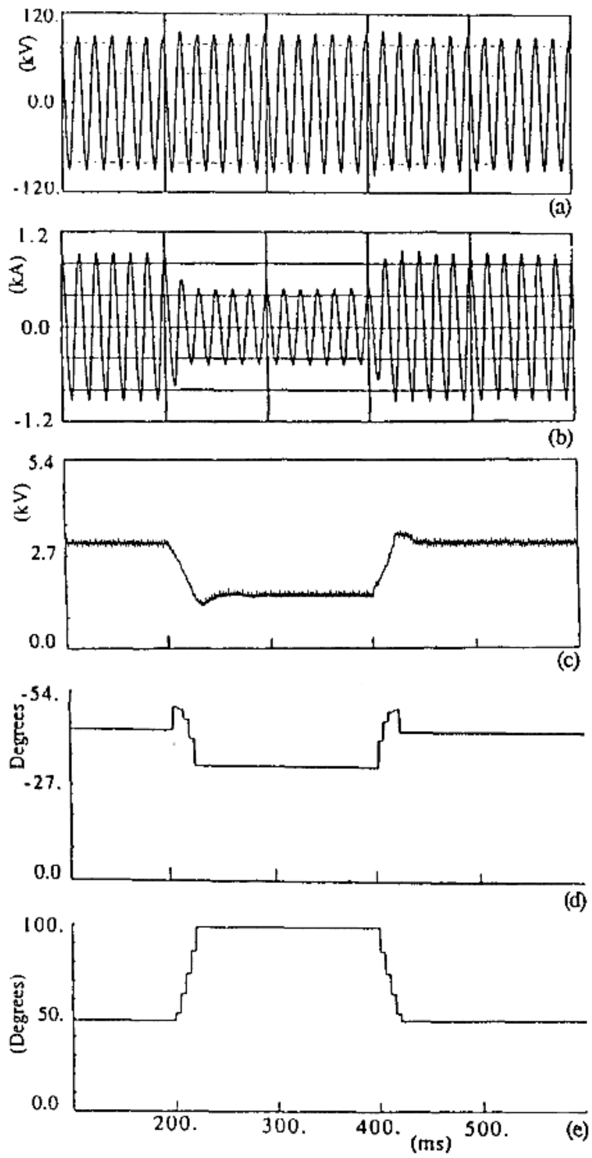


Figure 4 *Dynamic response to load change*
a) Phase a voltage
b) Phase a load current
c) DC voltage across the SMES coil
d) Firing angle delay of inverter one
e) Firing angle delay of inverter two

Figures 4a and 4b show phase a bus voltage and load current. Figure 4c shows the DC voltage across the SMES coil. The coil current for this study is constant at 30 kA. As expected, the coil voltage and ac current reflect the drop in the real power demand.

Figures 4d and 4e show how $\alpha 1$ and $\alpha 2$ change as the power demanded changes. As can be seen from figure 4d, the first converter is supplying P and Q both before and after the change in the load demand. However, the magnitude of the Q provided by this converter is decreased as the AC load drops by one half. Note that as the AC load demand drops, the amount of the reactive power supplied by the delta capacitors remains constant resulting in the reduction of Q provided by converter one. Figure 4e shows that the second converter is supplying P to the load and consuming Q before the change in the AC load. After the AC load drops, it consumes both power and reactive power from the ac system.

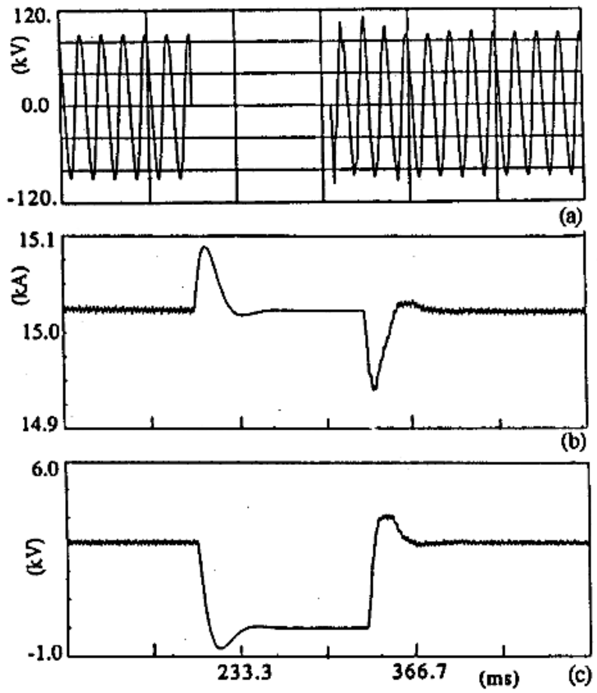


Figure 5 *Response to AC fault*
a) Phase a voltage
b) DC current through the coupled reactors
c) DC voltage across the SMES coil

Response of the Hybrid CSI to Faults
Figure 5 shows the response of the system to a three phase AC fault. The fault occurs at 200 ms with a duration of 100 ms. Figure 5a shows that the AC bus voltage is shorted during this period. Figure 5b shows that the disturbance to current balance in the coupling reactors is less that 1% which returns to the balanced case in a few milliseconds. Figure 5c shows the DC voltage across the coil.

As soon as the fault occurs, both of the CSIs bypass allowing the DC current to circulate through the GTOs. This is achieved by closing one pair of the valves connected to the same phase while opening the other two sets of valves connected to the other two phases in each converter. In this bypass mode, each of the CSIs look like a short circuit to the DC current sharing reactors and an open circuit to the AC delta capacitors. Figure 5b shows that the DC current through each converter remained constant through AC fault. Once the AC fault is cleared, the two CSIs are taken out of the bypass mode and continue their normal mode of operation.

Opening the Shorting Switch with the Hybrid CSI
In a storage mode the SMES coil current is circulating through a shorting switch. To provide power to the AC system the current of the coil must be transferred from the shorting switch to the converter as part of the start-up procedure.

Figure 6 shows how the system responds to this start-up procedure. In this figure, the hybrid converter operates as a rectifier from 10 ms to 14 ms. This operation uses power from the ac system to drive a counter current in the shorting switch which slowly brings the switch current to zero followed by the opening of the switch. During this same period the current sharing reactors achieve their nominal operating levels of current. See the dashed curve in Figure 6. for reactor current levels.

The start-up period ends when the current through the shorting switch reaches zero. At this point, both of the converters are carrying DC current at zero power. The system is ready to provide power to the ac system through the same procedures used in the recovery from a three phase fault.

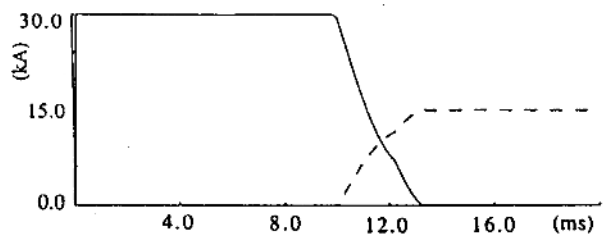


Figure 6 *Current through the shorting switch (solid line) and the current through the coupled reactors (dashed lines)*

VSI-Chopper

Figure 7 shows the model for a 100 MW VSI-Chopper system. Power is supplied to the AC system through a voltage sourced inverter (VSI). The VSI is linked to the coil through a dc capacitor and chopper. The chopper controls the current flow from the coil to the VSI.

The converter consists of two 50 MW 6-pulse voltage sourced inverters (VSI) connected in series on the AC side and in parallel on the DC side. The firing pulses of the two VSIs are phase shifted 30 degrees in order to simulated a pseudo 12-pulse VSI system. A pseudo 12-pulse is modelled to study the possible problems which could result from the full pseudo 24-pulse system discussed in reference [1].

The chopper is modelled as a two-quadrant three phase chopper with harmonic free duty cycle values of {0, 1/3, 2/3, 1}. Since the concept of harmonic free points are to be studied in

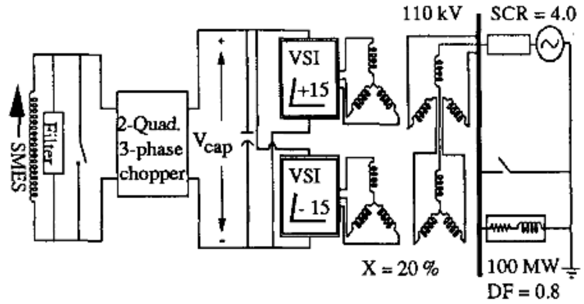


Figure 7 *Simulation model of a 100 MW VSI-Chopper system*

this case, the system parameters were initially chosen such that a duty cycle value of 1/3 corresponded to 100 MW power operation. Next, the power demanded was halved, which corresponds to a duty cycle value of 2/3.

Control Algorithm for the VSI-Chopper

The control algorithm of the VSI-chopper system is shown in Figure 8. The inputs are the real power (P), the displacement factor of the AC load (DF), the coil current (I_{smes}) and the magnitude of the AC bus voltage (E). The output values are duty cycle of the chopper (D) and α of the VSI. The firing delay α is the angle by which the 12-pulse converter output voltage leads the AC bus voltage. Additional internal variables are V_{cap}, D_{est} .and |V|.

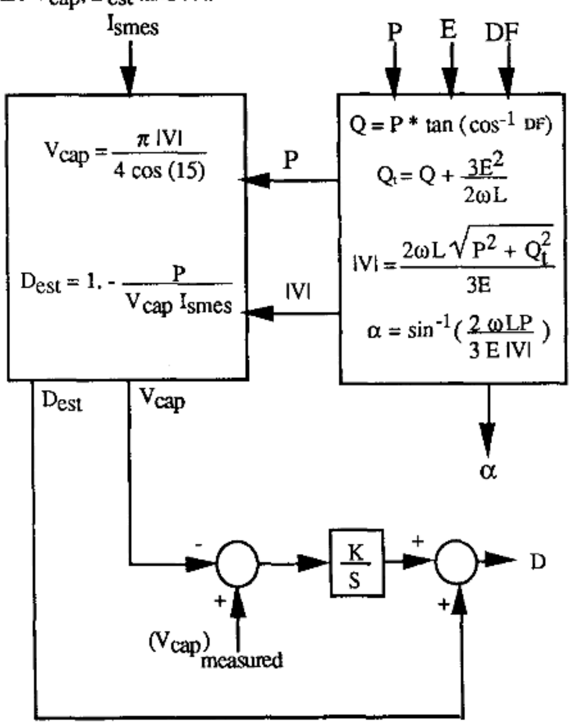


Figure 8 Control block diagram of the VSI Chopper System

V_{cap} is the DC voltage across the capacitor coupling the VSI to the chopper. D_{est} is the estimated duty cycle value of the chopper. |V| is the magnitude of the converter voltage on the converter side of the transformer. |V| and Vcap are related though the equation shown below. For a pseudo 12-pulse VSI system this equation is derived by adding the equations for a 6-pulse system with phase shifts of +15 and -15 degrees.

$$|V| = [2*V_{cap}/\pi]\cos(15) + [2*V_{cap}/\pi]\cos(-15.)$$

The control system is an open loop control on α and closed loop on V_{cap}. The value of α is calculated directly from the input values resulting in a firing angle which must be synchronized to the fundamental component of the AC bus voltage. On the other hand, the control system is a closed loop on V_{cap} to correct for calculation errors in D_{est}. This insures that the DC-DC chopper providing the desired DC voltage across the VSI In the closed loop operation, the value of the integrator gain K is important in determining the dynamics of the system. The value of the gain K used for simulations was 25.1, which was found by trial and error.

Dynamic Response to the AC load changes.

In this event, the real power demanded by the AC load drops from 100 MW to 50 MW and then returns to 100 MW two hundred milliseconds later while the displacement factor of the load is kept constant at 0.8.

Figures 9a and 9b show the AC bus voltage and AC load current. Figure 9c shows the DC voltage across the SMES coil. The coil current for this study is a constant value of 15 kA. As expected, the value of coil voltage drops by a factor of two as the real power demanded drops by the same factor. During this event the chopper crosses non-harmonic free points resulting in harmonics in the coil voltage. These harmonics could be avoided in a 58 phase system by constraining the duty cycle to harmonic free points.

Figure 9d shows the duty cycle of the chopper. As the AC load changes, a new value of the duty cycle is calculated using the control system of Figure 7. The underdamped behavior of the duty cycle is due to the closed loop control on V_{cap}. As can be seen from Figure 9e the DC voltage across the 12-pulse VSI tracks the reference voltage (shown by the doted curve) with the same underdamped response.

Figure 9f shows α which is the angle by which the 12-pulse convertor voltage leads the AC bus voltage. The control system is open loop resulting in an α which tracks the change in requested power.

Response of the VSI-Chopper to Faults

Figure 10 shows the response of the system to a three phase AC fault occurring at 300 ms for 100 ms. Figure 10a shows the AC bus voltage. As soon as the AC fault occurs all of the GTOs of the VSI are opened as their current becomes zero. This isolates the DC capacitor from the VSI and the AC system. In other words, the VSI looks like an open circuit to this capacitor. This event is represented by the zero VSI current in figure 10b.

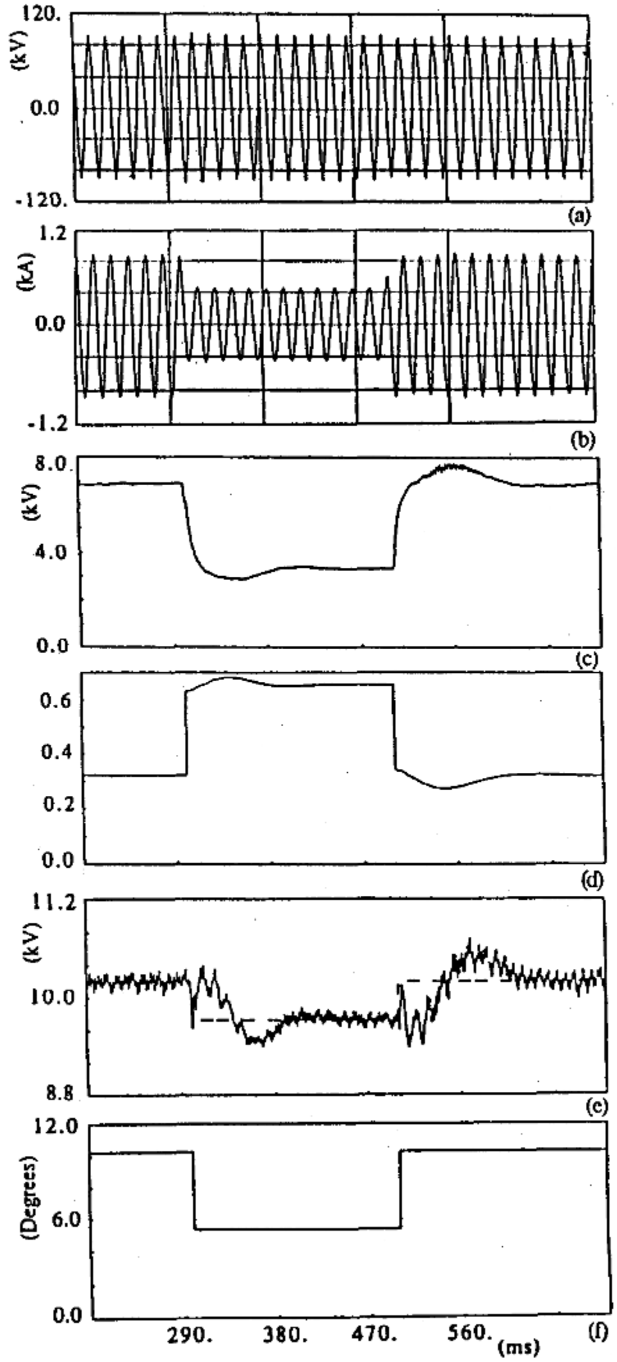
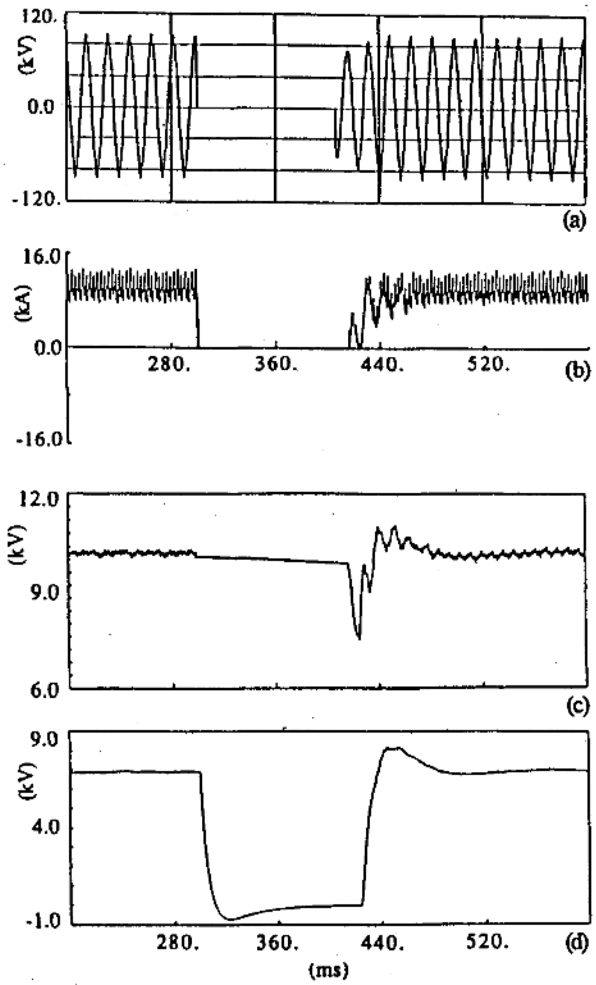


Figure 9 *Dynamic response to load change*
a) Phase a voltage
b) Phase a load current
c) SMES coil voltage
d) Duty cycle of the chopper
e) DC voltage across the 12-pulse VSI
f) Firing angle α, of the inverter

At the same time, the chopper shorts the SMES coil by firing one leg of the chopper, which then open circuits the chopper from the DC capacitor allowing the coil current to flow through the chopper legs. Note that the DC voltage across the capacitor in figure 10c remains charged and becomes harmonics free. However, this capacitor discharges slowly through the snubbers and if the fault remains long enough, the chopper should be used to recharge the capacitor before starting the system.

Figure 10d shows the DC voltage across the SMES coil. The coil voltage reaches zero during the fault and the dynamics of its transient is underdamped thus charging the coil for a short



a) Phase a voltage
b) VSI current
c) DC voltage across the 12-pulse VSI
d) SMES coil voltage

time. The energy used to charge the coil comes from the energy stored in the DC capacitor across the coil before the fault occurs. The system recovers from the fault at 400 ms followed by the VSI and the chopper resuming their normal modes of operation.

Figure 10c shows that the DC voltage across the capacitor linking the 12-pulse VSI to the chopper. During the restart procedure and the capacitor voltage drops by 25%. This drop is due to starting the VSI a few milliseconds sooner than the chopper. This drop of the DC voltage is critical in avoiding a large over voltage on the AC side.

Opening the Shorting Switch of the VSI-Chopper
Let us look at the storage mode in which the SMES coil current is circulating through the shorting switch. In this case, the current sharing reactors of the chopper carry no current and both the DC capacitor across the 12-pulse VSI and the DC capacitor across the SMES coil are not charged. Now the question is whether the PCS is capable of starting the system quickly without large transients. Figure 11 shows how the modelled system of Figure 7 is capable of this start-up procedure. The DC capacitor linking the VSI and the chopper is initially charged by closing the AC breakers to the 12-pulse VSI. The 12 anti-parallel diodes of the VSI behave like a 12-pulse diode rectifier which charges the capacitor. Figure 11 shows that this charging process takes 9 ms. Note that as soon as the voltage across the DC capacitor becomes greater than the line to line voltage on the AC side the 12 diodes of the VSI become reverse biased ending the charging process.

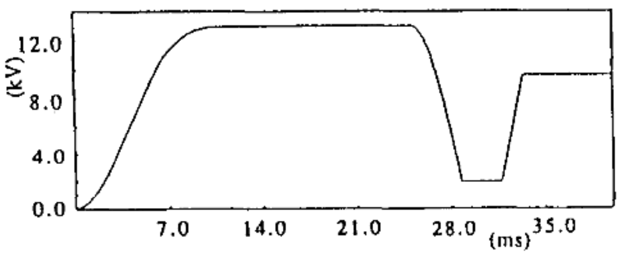


Figure 11 *DC voltage across the 12-pulse VSI*

Once the DC capacitor is charged, the energy stored in the DC capacitor is used to open the shorting switch. This process starts with the closure of the GTOs of the chopper which then initiates a 3 ms resonant cycle between the DC capacitor and the current sharing inductors. As a result, the current through the current sharing inductors evenly ramps up and the voltage across the DC capacitor ramps down.

Next, the chopper operates with a duty cycle value of zero for one millisecond in order to recharge the DC capacitor. Upon completion of this cycle, the value of the DC capacitor is charged to the desired value of 10 kV. At this point the chopper stops charging the capacitor and the system is ready to go through the same procedures as in recovery from a three phase fault.

Conclusion

The dynamic response of two new power conditioning systems for superconductive magnetic energy storage (SMES) were presented. One power conditioning system is based on a hybrid current sourced inverter (CSI), the second is a combination of a dc chopper with a voltage sourced inverter (VSI). The response of both systems to a load change, a three phase fault and start-up was presented in this paper. Both of the systems showed excellent response. The hybrid CSI is easier to control due to the presence of only one converter module. On the other hand, the VSI-chopper system allows a better control of harmonics. It is believed that both systems can be useful in future SMES applications.

Acknowledgments

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