CONCLUSIONS

A thyristor controlled Superconducting Magnetic Energy Storage (SMES) is a device that can very rapidly inject/absorb both real and/or reactive power into/from the power system to which the SMES is connected. Therefore, SMES is expected to posses a great potential for power system stabilization due to its inherent fast acting capability and high overall energy conversion efficiency. In order to illustrate the various concepts and design procedures evolved in this research work two systems have been considered for transient stability investigations namely single machine connected to infinite bus system and a multi-machine system. The results of the investigations related to the present research work reported in various chapters of this thesis are brought out in the following paragraphs.

In Chapter 1, the literature survey carried out related to the research is reported. The importance of need to carry out the research in the proposed field of study has been bought out. A clear roadmap for the proposed work along with the methodology to be adopted for research work has been indicated.

In Chapter 2, a versatile mathematical model of thyristor controlled SMES, suitable for transient stability investigations, was developed. The model incorporates a twelve pulse AC/DC converter used for power conversion, and has a provision for making a choice of suitable power system variables as a control signal for the SMES controller. The simulation of the system model has been carried out in MATLAB—a high-level technical computing language and interactive environment.

In Chapter 3, the transient stability investigations of SMIB system with SMES are presented. In order to quantify the improvement in the performance of SMES controllers, a performance index based on the integral square error (ISE) is defined. The parameters of controller are varied by discrete values to obtain minimum acceptable ISE for the defined performance index so as to provide the best setting of the controller with a constraint that the active power absorbed/released by SMES does not exceed the rating of SMES selected for the investigations of the given power system.
The effectiveness of deviation in rotor angle ($\Delta \delta$) and deviation in rotor angular velocity ($\Delta \omega$) for controlling the SMES device have been investigated. From the point of view practical implementation deviation in rotor angular velocity ($\Delta \omega$) is recommended as the most suitable signal for the SMES controller.

The effectiveness of Proportional type (P-SMES) and proportional-integral type (PI-SMES) controllers for SMES in controlling the transient swings of the system has been investigated for severe fault (three phase fault) at the bus where SMES is connected. It has been found that P-SMES is very effective for different loading conditions as well as for the conditions when the fault clearing time is greater than the critical fault clearing time for the system under investigations. It has been observed that the maximum swing of rotor angle is less when PI-SMES controller was used than that in case of P-SMES controller. However, the transient swings damp out in almost the same time duration in both the cases meaning thereby that the improvement in the settling time is not appreciable when PI-SMES is used in place of P-SMES controller. Thus, it is recommended that the Proportional-type controller for SMES (P-SMES) will be able to provide the desired damping of the system oscillations in transient stability studies.

In improving transient stability of a power system the performance of SMES is compared with that of a conventional dynamic brake, which is presently in use in western countries. It is observed that the performance of the system considered with SMES is better than that with optimally switched dynamic brake under similar operating conditions.

In order to keep the rating of SMES device as low as possible the fast acting circuit breaker should form an integral part of the power system. A novel approach to determine the capacity of the SMES device for a given power system has been developed in the present work. In this approach the active power output of generator at the instant of fault clearance is calculated. During the transient period, the value by which the electrical power output exceeds the constant mechanical power input from the prime mover is taken as the active power rating of SMES. This approach has been validated for a typical single machine connected to infinite bus.
In Chapter 4 the performance of Fuzzy Logic based SMES controller is investigated for SMIB system. Two fuzzy logic controllers namely Fuzzy Logic Controller for active power (FPC) and Fuzzy Logic Controller for reactive power (FQC) were developed. The deviation in rotor angle, $\Delta \delta$, and rotor relative angular velocity, $\Delta \omega$, are the inputs to FPC controller to obtain the estimated active power, whereas change in terminal voltage ($\Delta v$) and change in error in voltage ($\text{cev}$) were taken as input variables to FQC to obtain the estimated reactive power. To obtain the crisp value of output, centroid method was used because of its high degree of accuracy. The results indicate that the system damping with Fuzzy Logic based SMES controller is better than that with P-SMES controller. The settling time is much lesser with Fuzzy Logic based SMES controller when compared to that of P-SMES for different loading conditions as well as for fault clearance time higher than the critical fault clearing time.

In Chapter 5 transient stability investigations with artificial neural network (ANN) controlled SMES are carried out for SMIB system. To finalize the ANN structure, that is, number of neurons in hidden layer, mean square error ($\text{MSE}$) is taken as the deciding factor. For the training of the ANN $\Delta \omega$ and $\Delta v$ are input variables and the estimated active power $P_d$ and estimated reactive power $Q_d$ of the SMES were the desired output variable. ANN was trained for two set of training patterns and back-propagation method is used for its learning. The first set of training pattern was corresponding to the system representative condition and the second set of training patterns was obtained by using three typical operating conditions. The performance of the system with trained ANN controller with both the approaches was investigated for varying load and varying fault clearance time. It was observed that ANN controlled SMES has a better damping of transient swings than that of P-SMES controller, and the second set of training pattern has a better response than the first set of training pattern. It was found that with the increase in number of training patterns ANN was able to provide satisfactory stable operation of the system for almost all possible loading conditions as well as for higher fault clearance time.

In order to observe the effectiveness of various controllers in multi-machine environment the transient stability investigations have been carried out using a typical multi-machine power system where the SMES along with its controller is located on a bus, which requires it most. The investigations are reported in Chapter 6. It was
found that if the fault was created at bus number three (for the system studied) the critical clearing time was found out to be minimum. Accordingly bus number three where machine three is connected is the most prominent place where the SMES is to be located. It may be added that the P-SMES controller is tuned for the SMES located at bus three with a rating of about fifty percent of the capacity of the entire multi-machine power system under investigations. The effectiveness of Fuzzy Controlled SMES for multi-machine system has also been investigated. In this case also it is found that the performance of SMES with Fuzzy Control is much better than that with Proportional Control.

In Chapter 7 transient stability investigations are carried out with respect to a Neuro-Fuzzy logic based controller for the system considered. The Adaptive Neuro-Fuzzy Inference System (ANFIS) is used for carrying out these investigations. The deviation in rotor angle \( \Delta \delta \) and rotor relative angular velocity \( \Delta \omega \) are used as input variables for one of the Neuro-Fuzzy controller to obtain the estimated active power, whereas change in terminal voltage \( \Delta v \) and change in error in voltage \( e_v \) are taken as input variables for other Neuro-Fuzzy controller to obtain the estimated reactive power. For the training of the Neuro-Fuzzy controller data from the representative system condition was taken. For different loading conditions as well as for varying fault clearing time for representative condition the response of the system was found better for higher loading conditions with Neuro-Fuzzy controller than that of P-SMES. The ANFIS is used again for transient stability investigation of a multi-machine power system with Neuro-Fuzzy logic based controller. System response for critical fault clearing time with Neuro-Fuzzy controlled SMES was found to be better than that of P-SMES controller. Precisely the settling time of oscillations was less in case of Neuro-Fuzzy controlled SMES when compared to that with P-SMES controller.

At the end it may be summarized that the following major investigations have been carried out in the present research:

The procedures to tune various types of SMES controllers for maintaining transient stability of power system have been evolved. The performance of SMIB system with two types of controller namely Proportional type (P-SMES) and proportional-integral type (PI-SMES) controllers for the SMES has been investigated.
These investigations have been carried out for different loading conditions as well as for the conditions when the fault clearing time is greater than the critical fault clearing time for the system under investigations. The performance of SMIB system with these two types of controllers has been compared. Based on this comparison, P-SMES type of SMES controller has been taken as reference for purpose of determining the improvement in performance of power system due to the other types of SMES controllers considered in rest of the research work. Performance of SMES in improving transient stability of a power system is compared with a conventional dynamic brake, which is presently in use in western countries. Performance of Fuzzy Logic based SMES is investigated for single-machine connected to infinite bus and compared to that of P-SMES for different loading conditions as well as for fault clearance time higher than the critical fault clearing time. Transient stability investigations with artificial neural network (ANN) controlled SMES are carried out for single machine connected to infinite bus system for two sets of training patterns. Mean square error (MSE) is taken as the deciding factor for number of neurons and the number of hidden layers. Back-propagation method is used for the learning of ANN. The performance of the system with trained ANN controller with both the approaches was investigated for varying load conditions and varying fault clearance time and compared with that of P-SMES. For the transient stability investigations in multi-machine environment, the best location where the SMES device is to be connected is decided. For multi-machine environment, studies are carried out for P-SMES controller and Fuzzy Logic based SMES controller and compared. Transient stability investigations are carried out with respect to a Neuro-Fuzzy logic based controller for single machine connected to infinite bus system and multi-machine environment. The Adaptive Neuro-Fuzzy Inference System (ANFIS) is used for carrying out these investigations. Performance of Neuro-Fuzzy controller is compared with that of P-SMES controller. The simulation of system model has been carried out in MATLAB—a high-level technical computing language and interactive environment.

It may be added that the present research work has contributed to the following achievements:
• An extensive literature survey related to the field of SMES as great potential for power system stabilization has been carried out and documented.

• A twelve pulse AC/DC converter have been implemented in the system model for power system stabilization.

• A more straightforward approach to compute the dc current of superconducting coil has been used and is based on the system conditions immediately after the fault is cleared.

• An approach for making a choice of a suitable power system variable to be used as a control signal for the SMES controller has been developed.

• Explicit relationships have been incorporated for computing the values of firing angles of the converters used for power system stabilization through SMES controllers.

• A performance index based on the integral square error (ISE) is defined and has been used to quantify the improvement in the performance of different types of SMES controllers.

• A novel approach to determine the capacity of the SMES device for a given power system has been developed.

• Versatile mathematical models for transient stability investigation in respect of single machine connected to infinite bus as well as a multi-machine system, when an SMES device is equipped with different types of controllers based on the achievements mentioned above, have been developed.

• The procedures to tune the SMES controllers have been documented.

• An approach to decide the rating of the SMES device for stabilizing the power system subjected to large disturbances finds an appropriate place in this research work.
• The versatility of the various controllers using SMES device for power system stabilization has been established through investigations for typical power systems.

• The results of these investigations could be easily made use of for practical implementation straight on actual system made available for the said purpose or alternately could be applied on a system after validation through a micro-machine model system.

In respect of future work, it is proposed that investigations could be carried out for the application of SMES in coordinated approach in the presence of other FACTS devices for the improvement of transient stability of power system. The effect of static excitation system and electronic governors could also be included in these investigations. It is further recommended that the investigations could be carried out for improving the power conditioning of SMES device when used for maintaining transient stability of power system. In addition, other Neuro-Fuzzy approaches such as combination of RBF neural network and fuzzy controller could also form the important component of such investigations. Not withstanding the high cost of SMES as compared to other FACTS devices, SMES has a vast scope in operation and control of future power systems.