CHAPTER 3
TRANSIENT STABILITY INVESTIGATION OF SMIB SYSTEM WITH SUPERCONDUCTING MAGNETIC ENERGY STORAGE DEVICES

Transient stability investigations carried out on the basis of the mathematical model developed in chapter 2 for the Superconducting Magnetic Energy Storage (SMES) are presented in this chapter. These investigations include selection of proper control signal suitable for SMES. The performance of proposed controller for SMES is compared with optimally switched dynamic brake. The effect of fault-clearing time higher than the critical clearing time and that of various loading conditions on the performance of the proposed controller is also given.

3.1 Transient Stability Investigations of Single Machine Connected to Infinite Bus Equipped with SMES

A power system consists of a number of plants, each with several generators, widely spaced and interconnected amongst themselves by transmission networks, to form a power grid. The system load consists of a combination of synchronous motors, synchronous condensers, induction motors, lighting and heating devices and other loads. The stability of such a system usually concerns transmission of power from one group of synchronous machine to another. As a rule both group consists predominantly of generators. During disturbances the machines of each group swing together and is said to form a coherent group. For the purpose of analysis, each group can be replaced by one equivalent synchronous machine and assuming the system to be represented by a two-machine system for carrying out the transient stability investigations. If synchronism is lost, the machines of each group stay together, although they go out of step with the other group.

Because the behaviour of a two-machine system represents the behaviour of a multimachine system, at least qualitatively, and because the two-machine system is very simple in comparison to the multimachine system, which it represents, the two-machine system is extremely useful in describing the influence of various factors upon system stability. Usually the receiving end group of synchronous machines in such a representation is treated as an equivalent synchronous machine of constant
terminal voltage, zero internal impedance and infinite inertia, that is an infinite bus, whenever the capacity of the receiving end system is more than sending end group of synchronous machines by at least ten times. If this condition is not satisfied the finite inertia of the receiving end group of synchronous machines may be considered to improve the accuracy of calculations [26].

The effectiveness of SMES in improving transient stability of power system is first considered with reference to a two-machine representation of power systems. While carrying out the investigations the usual assumption are:

(i) Turbine power is kept constant.

(ii) A synchronous machine for transient stability studies is represented by constant transient internal emf $E'$ behind direct-axis transient reactance $x'_{d}$, which is a function of air-gap flux linkages.

A general schematic diagram of a simple power system consisting of a synchronous machine connected to infinite bus through a transformer and a double circuit transmission line is shown in Fig.3.1. The SMES is represented in the diagram by a variable shunt admittance $Y_{\text{smes}}$. The synchronous machine is represented by a constant source of internal emf $E'$ behind direct-axis transient reactance in series with transient reactance $x'_{d}$.

![Fig.3.1 Schematic Representation of a Simple Power System with SMES](image)

### 3.1.1 System Governing Equations

The swing equation of a synchronous machine during fault condition may be represented in state space form as:

$$\frac{d\Delta}{dt} = \Delta \omega = \omega - \omega_0$$  \hspace{1cm} (3.1)
The electrical power output of the generator is given by:

\[ P_e = |E'|^2 |Y_{11}| \cos(\theta_{11}) + |E'| |V_B| |Y_{12}| \cos(\theta_{12} - \delta') \]  \hspace{1cm} (3.3)

where,

\[ E' = |E'| \angle \delta' \hspace{0.5cm} V_B = |V_B| \angle 0^\circ \]

The swing equation of a synchronous machine during post-fault condition may be represented in state space form as:

\[ \frac{d\delta'}{dt} = \Delta \omega = \omega - \omega_c \] \hspace{1cm} (3.4)

\[ \frac{d\omega}{dt} = \frac{\pi f}{H} (P_t - P_e \pm P_{smes}) \] \hspace{1cm} (3.5)

The electrical power output of the generator is given by:

\[ P_e = |E'|^2 |Y_{11}| \cos(\theta_{11}) + |E'| |V_B| |Y_{12}| \cos(\theta_{12} - \delta') \] \hspace{1cm} (3.6)

where,

\[ E' = |E'| \angle \delta' \hspace{0.5cm} V_B = |V_B| \angle 0^\circ \]

\[ P_{smes} = V_{do} I_d (\cos \alpha_1 + \cos \alpha_2) \] \hspace{1cm} [46,111] \hspace{1cm} (3.7)

where,

\[ V_{do} = \frac{3\sqrt{2}}{\pi} E \] \hspace{1cm} (3.8)

\[ \alpha_1 = \cos^{-1}\left(\frac{P_d}{\sqrt{P_d^2 + Q_d^2}}\right) - \cos^{-1}\left(\frac{\sqrt{P_d^2 + Q_d^2}}{2V_{do} I_d}\right) \] \hspace{1cm} (3.9)

\[ \alpha_2 = \cos^{-1}\left(\frac{P_d}{\sqrt{P_d^2 + Q_d^2}}\right) + \cos^{-1}\left(\frac{\sqrt{P_d^2 + Q_d^2}}{2V_{do} I_d}\right) \] \hspace{1cm} (3.10)
where,
\[ P_d = f_1 (\Delta \omega) \]  \hspace{1cm} (3.11)
\[ Q_d = f_2 (\Delta v) \]  \hspace{1cm} (3.12)

where,
\[ \Delta \omega \]  may be equal to \( \Delta \omega, \Delta p, \Delta c \)
\[ \Delta v \]  change in voltage

To insert for proportional type of controller with speed signal its input \( P_d \) and \( Q_d \) are given by:
\[ P_d = k_{\omega} \Delta \omega \]  \hspace{1cm} (3.13)
\[ Q_d = k_{v} \Delta v \]  \hspace{1cm} (3.14)
\[ I_d = (P_e - P_T)/V_{do} \]  \hspace{1cm} (3.15)
\[ Q_{smes} = V_{do} I_d (\sin \alpha_1 + \sin \alpha_2) \]  \hspace{1cm} (3.16)
\[ Y_{smes} = G_{smes} + j \omega_{smes} = \frac{P_{smes} \omega_{smes}}{|V_i|^2} - j \frac{Q_{smes} \omega_{smes}}{|V_i|^2} \]  \hspace{1cm} (3.17)

This relationship is used to obtain \( \Delta v \) signal at every step of numerical integration system differential equations in the mathematical model.

where,
\[ P_e \]  electrical power output of generator in p.u. at the instant of fault clearance
\[ P_T \]  turbine power in p.u.
\[ \delta' \]  phase angle between \( E' \) and infinite bus voltage \( V_b \) in electrical radians
\[ \omega \]  rotor angular velocity in electrical radians per second
\[ \omega_0 = 2 \pi f_o \] , the steady state angular velocity in electrical radians per second
\[ f_o \]  60 Hz , the nominal frequency
\[ H \]  per unit inertia constant in seconds
\[ V_{do} \]  the ideal no-load maximum DC voltage of the 6-pulse bridges
\[ V_d \]  average dc voltage impressed on the superconducting coil by the converter
$Y_{smes}$ admittance of superconducting coil
$B_{smes}$ susceptance of superconducting coil
$G_{smes}$ conductance of superconducting coil
$E$ the voltage on the secondary side of the transformer or the bus voltage at which the SMES is connected
$\alpha_1$ firing delay angle of converter 1
$\alpha_2$ firing delay angle of converter 2
$I_d$ unidirectional dc current flowing in the superconducting coil
$P_{smes}$ active power absorbed/released by superconducting coil
$Q_{smes}$ reactive power absorbed/released by superconducting coil
$S_{smes}$ electric MVA power absorbed/released by superconducting coil
$V_t$ terminal voltage of synchronous machine
$P_d$ estimated active power of SMES
$Q_d$ estimated reactive power of SMES
$|Y_{11}|$ magnitude of driving point admittance of the synchronous machine in p.u.,
$\theta_{11}$ admittance angle associated with $Y_{11}$ in radians,
$|Y_{12}|$ magnitude of transfer admittance between the synchronous machine and infinite bus in p.u.
$\theta_{12}$ admittance angle associated with $Y_{12}$ in radians

The Eq. (3.1), Eq. (3.2) and Eq. (3.3), Eq. (3.4) may be solved using numerical methods such as modified Euler method, Runge Kutta etc. [9,32,33,129]

3.2 System Considered for Transient Stability Investigations

The schematic diagram of the sample system considered for stability studies with SMES connected to the generator terminal is shown in Fig 3.2. The system consists of synchronous generator having a terminal voltage $V_t$ connected to a local load $(G_L+jB_L)$, where $G_L$ and $B_L$ are the conductance and susceptance respectively of the local load. The generator terminal is connected to an infinite bus having constant voltage $V_B$ through a transformer and a double circuit transmission line. Transformer
has reactance $X_l$ and each line has impedance $(R_l + jX_l)$. The SMES connected to the
generator terminal is represented in the diagram by $G_{smes} + jB_{smes}$.

![Diagram of the system considered for transient stability investigations]

Fig. 3.2 Schematic Representation of the System Considered for Transient Stability Investigations

Infinite bus voltage is chosen as the reference phasor for transient stability investigations.

With reference to Fig. 3.2 the system data in p.u. is as follows [14,37]:

\[
\begin{align*}
X_d &= 1.0; & G_L + jB_L &= 0.18 + j 0.067; \\
X_q &= 0.6; & S &= 0.753 + j 0.03; \\
X_d' &= 0.27; & |V_l| &= 1.05; \\
X_l &= 0.13; & |E'| &= 1.075; \\
R_L &= 0.15; & |V_B| &= 1.0; \\
X_L &= 0.7488; & H &= 4 \text{ secs}; \\
R &= 5.5; & T_{do} &= 9 \text{ secs}; \\
TRC &= 0.4 \text{ secs}; & TFC &= 0.2 \text{ secs};
\end{align*}
\]

3.3 Performance Index

In order to compare the performance of the system considered when provided with different types of controllers as well as control signals it is necessary to evolve and establish a criteria for obtaining the best value of the gain settings of the controller. Wherever required it is the usual practice to use integral square error (ISE) as performance index to investigate the effectiveness of the given controller and compare its performance for the various settings. The setting which gives the
minimum acceptable integral square error for the given performance index is considered as the best setting of the controller. The performance index used in the present investigation is given by

\[
\text{Performance Index} = \frac{1}{T_c} \int_0^T [(\Delta \omega)^2 + (\Delta v)^2] dt
\]

(3.18)

where, \(\Delta \omega, \Delta v\) has their usual meaning and \(T_c\) is the total computation time

3.4 Transient Stability Investigations of System Considered Using Proportional Type SMES Controller

A three-phase fault is assumed at the sending end of one of the transmission lines and the fault is assumed to be cleared by opening of faulted line. The swing curves for different times of fault clearance are shown in Fig. 3.3 without any stability improvement device for different fault clearing times. From the swing curves of Fig.3.3 it is clear that the critical fault clearing time for the given fault specified above is 0.2 secs.

Fig 3.3 Swing curves for the synchronous machine for different values of \(TFC\)
Swing curves have been computed for fault clearing time $TFC = 0.21667$ seconds. The system turned out to be unstable for this fault clearing time is shown in Fig. 3.3. In order to determine the effectiveness of SMES, it is assumed that the SMES connected to the terminals of the synchronous machine immediately after the fault clearance. The operation of SMES is controlled by controlling triggering delay angle of bridge converter as discussed earlier in section 2.3. Two types of signals are available for the control of firing angle of converters of the SMES. The signal may be rotor angle deviation $\Delta \delta$, rotor relative angular velocity $\Delta \omega$, and change in voltage $\Delta v$. The regulation laws are given below:

**Case (i) $\Delta \delta$ as control signal**

$$P_d = k_d \cdot \Delta \delta$$

(3.19)

$$Q_d = k_v \cdot \Delta v$$

(3.20)

**Case (ii) Rotor relative angular velocity as control signal**

$$P_d = k_{\omega} \cdot \Delta \omega$$

(3.21)

$$Q_d = k_v \cdot \Delta v$$

(3.22)

where,

$\Delta \delta$  rot or angle deviation

$\Delta v$  change in terminal voltage of synchronous machine in p.u.

$\Delta \omega$  rotor relative angular speed , rad/sec

$\Delta P$  change in active power

$k_d$  gain coefficient for acceleration as control signal

$k_{\omega}$  gain coefficient for rotor relative speed as control signal

$k_P$  gain coefficient for change in active power as control signal

$k_v$  gain coefficient for change in terminal voltage of synchronous machine as control signal

The swing curves with the SMES connected to the system in operation, during post-fault condition, have been computed for the two types of regulation of SMES mentioned above in Eq. 3.19 to Eq. 3.22. The transient stability studies are carried for two different fault clearing times.
(i) Case I: $TFC = 0.2$ secs (Critical Fault Clearing Time)

(ii) Case II: $TFC = 0.21667$ secs (Beyond Critical Fault Clearing Time).

### 3.4.1 Transient Stability Investigations of SMIB with System Considered using Proportional Type SMES Controller for Critical Fault Clearing Time

The effectiveness of different control signals of SMES in damping transient oscillations of rotor angle caused by large disturbances is discussed for fault clearing time $TFC = 0.2$ secs. The gain coefficients $k_d, k_m, k_v$ for different control signals for the above stability studies are varied to find the best value of the gain coefficients.

#### 3.4.1.1 Rotor Angle Deviation as Control Signal ($\Delta \delta$)

The gain coefficient $k_d$, when the $\Delta \delta$ is used as signal, is varied from a very low value of 0.01 to 0.07 for case I, while keeping the gain coefficient $k_v$ fixed at a constant value of 0.5. The corresponding swing curves are shown in Fig. 3.4. It may be seen from Fig. 3.4 that the maximum value of $\delta'$ decreases as the value of $k_d$ is increased. The decrease in maximum value of swing is significant. It may further be noted that the damping of oscillations is greatly improved with the increase in the value of $k_d$. The rotor angle oscillations are fully damped in approximately in 3.0 seconds.

In order to fix the rating of SMES it is pertinent to plot the active power inflow/outflow from SMES when used to enhance transient stability of the power system. These variations are shown in Fig. 3.5 for the various values of $k_d$ when proportional controller is used with $\Delta \delta$ as its input stabilizing signal. The curves indicate that active power rating of 0.5 p.u. of SMES will be sufficient.

The variation of the performance index in this case for various values of $k_d$ is shown in Fig. 3.6. For active power limit of 0.5 p.u. for the SMES the minimum value of performance index is available at $k_d = 0.07$. Accordingly this value of $k_d$ comes out to be the best gain value for the proportional controller.
Fig. 3.4 The effect of variation of $k_d$ for $TFC = 0.2$ secs and $k_v = 0.5$ on rotor angle $\delta'$. 

Fig. 3.5 The effect of variation of $k_d$ for $TFC = 0.2$ secs and $k_v = 0.5$ on active power requirement of SMES.
3.4.1.2 Rotor Relative Angular Speed as Control Signal ($\Delta \omega$)

The gain coefficient $k_{\omega}$ is varied from 0.01 to 0.07 for case I, keeping the gain coefficient $k_r$ at a constant value of 0.5. The corresponding swing curves are shown in Fig. 3.7. It may be seen from Fig. 3.7 that the maximum value of $\delta'$ decreases as the value of $k_{\omega}$ is increased. It may be noted that the damping of oscillations is greatly improved with the increase in the value of $k_{\omega}$. The rotor angle oscillations are fully damped in approximately 3.0 seconds.

In order to fix the rating of SMES it is pertinent to plot the active power inflow/outflow from SMES when used to enhance transient stability of the power system. These variations are shown in Fig. 3.8 for the various values of $k_{\omega}$ when proportional controller is used with $\Delta \omega$ as its input stabilizing signal. The curves indicate that active power rating of 0.5 p.u. of SMES will be sufficient. Even though
the active power requirement of SMES in the case is slightly lesser in magnitude than that in case of $\Delta \delta$ as control signal, the SMES active power requirement may be kept at 0.5 p.u. in this case as well.

The variation of the performance index in this case for various values of $k_\omega$ is shown in Fig. 3.9. For active power limit of 0.5 p.u. for the SMES the minimum value of performance index is available at $k_\omega = 0.07$. Accordingly this value of $k_\omega$ comes out to be the best gain value for the proportional controller using $\Delta \omega$ as control signal.

![Figure 3.7](image_url)

Fig. 3.7 The effect of variation of $k_\omega$ for $TFC = 0.2$ secs and $k_v = 0.5$ on rotor angle $\delta'$
Fig. 3.8 The effect of variation of $k_w$ for $TFC = 0.2$ secs and $k_v = 0.5$ on active power requirement of SMES.

Fig. 3.9 The effect of variation of $k_w$ for $TFC = 0.2$ secs and $k_v = 0.5$ on Performance Index.
3.4.1.3 Comparison of System Performance with different Control Signals for Critical Fault Clearing Time

For the purpose of comparison, the swing curves obtained corresponding to the best values of gain settings for $\Delta \delta$ and $\Delta \omega$ as control signals are given in Fig.3.10. The variations of performance index in these cases are shown in Fig. 3.11. Since the variation of swing curves in both the cases are very close, accordingly these two signals namely $\Delta \delta$ and $\Delta \omega$ appears to be alternative to each other. On the other hand it is well known that from implementation point of view $\Delta \omega$ signal is preferred.

Fig 3.10 Comparison of $\Delta \delta$ and $\Delta \omega$ signals for best values of $k_d$, $k_w$, and $k_v$ for $TFC = 0.2$ secs
The effectiveness of different control signals of SMES in damping transient oscillations of rotor angle caused by large disturbances is discussed for fault clearing time $TFC = 0.21667$ secs. The gain coefficients $k_d$, $k_\omega$, and $k_v$ for different control signals for the above stability studies are varied to find the best value of the gain coefficients.

### 3.4.2.1 Rotor Angle Deviation as Control Signal ($\Delta \delta$)

For case II the gain coefficient $k_d$ is varied over the same range, while keeping the gain coefficient $k_v$ at a constant value of 0.5. The corresponding swing curves are shown in Fig.3.12. It may be seen from Fig.3.12 that the maximum value of $\delta'$ decreases as the value of $k_d$ is increased. The decrease in maximum value of swing is significant. It may further be noted that the damping of oscillations is greatly
improved with the increase in the value of $k_d$. The rotor angle oscillations are fully damped in approximately in 3.0 secs. The results obtained are similar to that in case I. It may be noted that the proportional controller using $\Delta \delta$ as control signal for SMES is able to stabilize and damp significantly the rotor oscillations of the otherwise unstable system where the fault is cleared after the critical fault clearing time.

In order to fix the rating of SMES in this case it is pertinent to plot the active power inflow/outflow from SMES when used to enhance transient stability of the power system. These variations are shown in Fig. 3.13 for the various values of $k_d$ when proportional controller is used with $\Delta \delta$ as its input stabilizing signal. The curves indicate that active power rating of 0.5 p.u. of SMES will be sufficient.

The variation of the performance index in this case for various values of $k_d$ is shown in Fig. 3.14. For active power limit of 0.5 p.u. for the SMES the minimum value of performance index is available at $k_d = 0.07$. Accordingly this value of $k_d$ comes out to be the best gain value for the proportional controller.

![Fig. 3.12 The effect of variation of $k_d$ for TFC = 0.21667 secs and $k_y = 0.5$ on rotor angle $\delta''$](image-url)
Fig. 3.13 The effect of variation of $k_w$ for $TFC = 0.21667$ secs and $k_v = 0.5$ on power requirement of SMES

Fig. 3.14 The effect of variation of $k_w$ for $TFC = 0.21667$ secs and $k_v = 0.5$ on Performance Index
3.4.2.2 Rotor Relative Angular Speed as Control Signal ($\Delta \omega$)

The gain coefficient $k_{w}$ is varied over the same range as in case I, keeping the gain coefficient $k_{e}$ at a constant value of 0.5. The corresponding swing curves are shown in Fig. 3.15. It may be seen from Fig. 3.15 that the maximum value of $\delta'$ decreases as the value of $k_{w}$ is increased and damping of oscillations is greatly improved with the increase in the value of $k_{w}$. The complete damping of oscillations is achieved in approximately 3.0 secs. It is observed that even for fault clearance time greater than the critical fault clearance time the system stability is maintained. Thus it may be concluded that SMES improves the stability of the system significantly.

In order to fix the rating of SMES it is imperative to plot the active power inflow/outflow from SMES when used to enhance transient stability of the power system. These variations are shown in Fig. 3.16 for the various values of $k_{w}$ when proportional controller is used with $\Delta \omega$ as its input stabilizing signal. The curves indicate that active power rating of 0.5 p.u. of SMES will be sufficient. Even though the active power requirement of SMES in the case is slightly lesser in magnitude, the SMES active power requirement is kept at 0.5 p.u. also.

The variation of the performance index in this case for various values of $k_{w}$ is shown in Fig. 3.17. For active power limit of 0.5 p.u. for the SMES the minimum value of performance index is available at $k_{w} = 0.07$. Accordingly this value of $k_{w}$ comes out to be the best gain value for the proportional controller.
Fig. 3.15 The effect of variation of \( k_\omega \) for \( TFC = 0.21667 \) secs and \( k_y = 0.5 \) on rotor angle \( \delta' \).

Fig. 3.16 The effect of variation of \( k_\omega \) for \( TFC = 0.21667 \) secs and \( k_y = 0.5 \) on active power requirement of SMES.
3.4.2.3 Comparison of System Performance for different Control Signals for Fault Clearing Beyond Critical Fault Clearing Time

For the purpose of comparison, the swing curves obtained corresponding to the best values of gain settings for $\Delta \delta$ and $\Delta \omega$ as control signals are given in Fig. 3.18 where as for performance index are in these cases are shown in Fig. 3.19 for clearing of fault at $TFC$ equal to 0.21667 secs. Since the variation of swing curves in both the cases are very close, accordingly these two signals namely $\Delta \delta$ and $\Delta \omega$ appears to be alternative to each other. It may be observed from Fig. 3.19 that the performance index is lower in magnitude when $\Delta \omega$ is used as a control signal. On the other hand it is well known that from implementation point of view $\Delta \omega$ signal is more convenient. Accordingly rotor relative angular velocity is considered as control signal for all further investigations.

Through investigations it has been observed that variation in the gain coefficient $k_v$ provided for the control of reactive power. It has negligible effect on rotor oscillations.
Fig 3.18 Comparison of $\Delta \delta$ and $\Delta \omega$ signals for best values of $k_d$, $k_\omega$, and $k_v$ for $TFC = 0.21667$ secs

Fig 3.19 Comparison of Performance Index for $\Delta \delta$ and $\Delta \omega$ signals for best values of $k_d$, $k_\omega$, and $k_v$ for $TFC = 0.21667$ secs
3.4.2.4 Conclusion

The transient stability investigations of SMIB where proportional type SMES controller have been carried out and presented in the preceding paragraphs. The results have indicated that a control signal proportional to $\Delta \omega$ is very effective in maintaining the transient stability of the system considered even the fault is cleared after critical fault clearing time. Before the Proportional-Integral controller configuration is considered for investigations it seems worth while to bring out the finer advances of the nature variations in SMES active power inflow/outflow as affected by the proportional controller using $\Delta \omega$ as the control signal.

Fig. 3.20 shows the variation of the control signal $\Delta \omega$ with respect to time, for $TFC=0.21667$ and $k_\omega = 0.07$. The self-regulating property of the device is clear from the curves of Fig. 3.20 showing variation of $\Delta \omega$ with respect to time and Fig. 3.21 showing variation of active power absorbed or delivered by SMES with respect to time. Point - a on the curve corresponds to the instant of fault clearance and from this very moment SMES comes into operation. The SMES continues to operate till $\Delta \omega$ becomes zero. For positive values of $\Delta \omega$ i.e. for time period from point-a to point-b, point-c to point-d and point-e to point-f in Fig.3.20 it acts as load and absorbs the active power from the system. It is shown in Fig 3.21 as positive value of $P_{smes}$ for time period from point - a to point - b, point-c to point-d and point-e to point-f. For negative values of $\Delta \omega$ i.e. for time period from point-b to point-c and point-d to point-e the SMES injects the power to the system. It is observed from Fig.3.21 that for time period from point-b to point-c and point-d to point-e, $P_{smes}$ is negative which implies that $P_{smes}$ is injected into the system. And finally when $\Delta \omega$ becomes zero, the SMES gets automatically switched off, the rotor oscillations are fully damped out. Thus application of SMES with $\Delta \omega$ control is very effective in improving transient stability of the system.
Fig. 3.20 Variation of $\Delta \omega$ signal at $TFC = 0.21667$ secs for P-SMES

Fig. 3.21 Variation of $P_{mes}$ at $TFC = 0.21667$ secs for P-SMES
3.5 Transient Stability Investigations of System Considered using Proportional Integral (PI- SMES) Controller

The block diagram representation of PI controller of SMES is given in Fig. 3.22. The controller uses rotor relative angular velocity, $\Delta \omega$, as the control signal. The governing equations for the controller are given below:

$$P_d = k_\omega \Delta \omega + k_i \int \Delta \omega \, dt$$

where,

- $sT_i >> 1$
- $Q_d = k_v \Delta \nu$
- $T_i$ = controller time constant, 5.0 secs

3.5.1 Transient Stability Investigations of SMIB with System Considered using Proportional – Integral (PI- SMES) Controller for Critical Fault Clearing Time

For $TFC = 0.2$ secs for the best values of gain coefficient $k_\omega = 0.07$ and $k_v = 0.5$ are taken for PI-SMES type of controller. The active power rating of SMES as determined in the preceding paragraphs is taken as 0.5 p.u. The gain constant $k_i$ is varied from 0 to 30. The effect of variation of $k_i$ is shown in Fig.3.23. It is observed that swing amplitude decreases as the value of $k_i$ is increased. For $k_i$ higher than 30,
there is no significant decrease in amplitude of swing. Therefore it can be seen from Fig. 3.23 that for $TFC = 0.2$ secs the best value of gain $k_j$ may be taken 30.

The variation of the performance index in this case for various values of $k_j$ is shown in Fig. 3.25. For active power limit of 0.5 p.u. for the SMES the minimum value of performance index is available at $k_j = 30$. Accordingly this value of $k_j$ comes out to be the best gain value for the proportional-integral controller.

Fig. 3.23 The effect of variation of $k_j$ for $TFC = 0.2$ secs on rotor angle
Fig. 3.24 The effect of variation of $k_t$ for $TFC = 0.2$ secs on active power requirement of SMES.

Fig. 3.25 The effect of variation of $k_i$ for $TFC = 0.2$ secs on Performance Index.
3.5.2 Transient Stability Investigations of SMIB with System Considered using Proportional–Integral (PI- SMES) Controller beyond Critical Fault Clearing Time with Synchronous Transient Stability

For $TFC = 0.21667$ secs for the best values of gain coefficient $k_0 = 0.07$ and $k_y = 0.5$ are taken for PI-SMES type of controller. The active power rating of SMES as determined in the preceding paragraphs is taken as 0.5 p.u. The gain constant $k_i$ is varied from 0 to 30. The effect of variation of $k_i$ is shown in Fig. 3.26. It is observed that swing amplitude decreases as the value of $k_i$ is increased. For $k_i$ higher than 30, there is no significant decrease in the amplitude of swing. Therefore, from Fig. 3.26 the best value of gain $k_i$ for $TFC = 0.21667$ secs may be taken as 30.

The variation of the performance index in this case for various values of $k_i$ is shown in Fig. 3.28. For active power limit of 0.5 p.u. for the SMES the minimum value of performance index is available at $k_i = 30$. Accordingly this value of $k_i$ comes out to be the best gain value for the proportional – integral controller.

![Graph](image_url)

Fig. 3.26 The effect of variation of $k_i$ for $TFC = 0.21667$ secs on rotor angle
Fig. 3.27 The effect of variation of $k_i$ for $TFC = 0.21667$ secs on active power requirement of SMES.

Fig. 3.28 The effect of variation of $k_i$ for $TFC = 0.21667$ secs on Performance Index.
3.5.3 Conclusion

The transient stability investigations of SMIB where proportional-integral SMES controller have been carried out and presented in the preceding paragraphs. The results have indicated that a control signal proportional to $\Delta \omega$ is very effective in maintaining the transient stability of the system considered even when the fault is cleared after critical fault clearing time. The nature of variations in SMES active power inflow/outflow as affected by the Proportional-Integral controller using $\Delta \omega$ as the control signal is shown in Fig. 3.30.

Fig. 3.29 shows the variation of the control signal $\Delta \omega$ with respect to time, for $TFC=0.21667$ and $k_\omega = 0.07$. The self-regulating property of the device is clear from the curves of Fig. 3.29 showing variation of $\Delta \omega$ with respect to time and Fig.3.30 showing variation of active power absorbed or delivered by SMES with respect to time. Point - a on the curve corresponds to the instant of fault clearance and from this very moment SMES comes into operation. The SMES continues to operate till $\Delta \omega$ becomes zero. For positive values of $\Delta \omega$ i.e. for time period from point-a to point-b, point-c to point-d and point-e to point-f in Fig.3.29 it acts as load and absorbs the active power from the system. It is shown in Fig.3.30 as positive value of $P_{\text{snes}}$ for time period from point - a to point - b, point-c to point-d and point-e to point-f. For negative values of $\Delta \omega$ i.e. for time period from point-b to point-c and point-d to point-e the SMES injects the power to the system. It is observed from Fig.3.30 that for time period from point-b to point-c, point-d to point-e and point-f to point-g $P_{\text{snes}}$ is negative which implies that $P_{\text{snes}}$ is injected into the system. And finally when $\Delta \omega$ becomes zero, the SMES gets automatically switched off, the rotor oscillations are fully damped out. Thus application of SMES with $\Delta \omega$ control is very effective in improving transient stability of the system.
Fig. 3.29 Variation of $\Delta \omega$ signal at $TFC = 0.21667$ secs for PI-SMES

Fig. 3.30 Variation of $P_{smes}$ at $TFC = 0.21667$ secs for PI-SMES
3.6 Comparison of System Performance with P-SMES and PI-SMES Controller

The comparative study of swing curves corresponding to the best value of gain coefficients $k_m = 0.07$, $k_v = 0.5$ and $k_i = 30$ obtained so far is made.

3.6.1 Comparison of System Performance with P-SMES and PI-SMES Controller for Critical Fault Clearing Time

From Fig 3.31 for $TFC = 0.2$ secs it may be observed that with PI-SMES type controller, the maximum swing with best values of $k_m$, $k_v$ and $k_i$ occurs at $\delta = 93$ degrees and with P-SMES type it occurs at $\delta = 97$ degree. However, the settling time in both the cases is almost same and has value of approximately 3.0 secs.

![Fig. 3.31 Comparison of Proportional-SMES and Proportional-Integral-SMES for $TFC = 0.2$ secs](image-url)
3.6.2 Comparison of System Performance with P-SMES type and PI-SMES type Controller for Fault Clearing Time Higher than Critical Fault Clearing Time

From Fig 3.33 for $TFC = 0.21667$ secs it may be observed that with PI-SMES type controller, the maximum swing with best values of $k_{on}$, $k_v$ and $k_i$ occurs at approximately $\delta' = 108$ degrees and with P-SMES type at $\delta' = 93$ degrees. The settling time in both the cases is almost same and is approximately 3.0 seconds.
Fig. 3.33 Comparison of Proportional-SMES and Proportional-Integral-SMES for $TFC = 0.21667$ secs

Fig. 3.34 Comparison of Proportional-SMES and Proportional-Integral-SMES for $TFC = 0.21667$ seconds
3.6.3 Conclusion

From Fig. 3.31 and Fig. 3.33 it is observed that settling time in both the cases is almost same. The maximum swing of rotor angle is less in case of Proportional-Integral-SMES as compared to Proportional-SMES. Proportional law of regulation being simpler, P-SMES type controller has been used for subsequent analysis.

3.7 Comparison of System Performance with Optimally Switched Dynamic Brake and SMES

The effectiveness of a SMES in damping out transient swings has already been established in the earlier sections. However, it is not known how effective a SMES is in improving transient stability of a power system compared to a conventional dynamic brake presently in use [21,37]. While attempting comparison with a conventional brake it is thought fit to compare it with the best designed conventional dynamic brake available. With this in mind the performance of the P-SMES is compared with that of an optimally switched conventionally dynamic brake suggested by Minisey et al [14]. As such the transient stability computations have been carried out with reference to the system given by Minisey [14]. It may be added that the system considered for investigations to find the effectiveness of a SMES in damping out transient swings is by Minisey [14] itself. The system simulation for obtaining system responses using an optimally switched conventionally dynamic brake were carried out by author using MATLAB.

Conventional dynamic brake is assumed to be connected to the terminals of the synchronous machine soon after the clearance of the fault and is disconnected after an optimum time interval determined in ref. [14]. For a fault clearance time of $TFC = 0.2$ sec, the optimal inclusion time of the dynamic brake with $R = 5.5$ per unit as reported by Minisey et.al [14] is 0.3 sec (or in other words the time of disconnection of the dynamic brake is $TBR = 0.5$ sec, the time measured from the time of incidence of fault). The corresponding curve for optimally switched dynamic brake are shown by curve-b in Fig.3.35 for $TFC = 0.2$ secs and for $TFC = 0.21667$ secs in Fig.3.36.
Fig. 3.35 shows the comparison of swing curves in three cases namely without any stabilizing device, with optimally switched dynamic brake and with P-SMES. In Fig.3.35 curve -a corresponds to the case when no dynamic brake is applied to the system, curve-b corresponds to the case when conventional dynamic brake is applied for an optimal time. Curve-c shows swing curve with P-SMES in operation with $k_w = 0.07$ and $k_y = 0.5$. It may be seen from the curves of Fig.3.35 and Fig.3.36 that P-SMES offers a much better control in damping rotor oscillations caused by the fault compared to an optimally switched dynamic brake.

Fig. 3.35 Performance comparison of Optimally Switched Dynamic Brake and SMES for at $TFC = 0.20$ secs
3.8 Performance of P-SMES for Fault Clearance Time Higher than Critical Clearing Time

The effectiveness of SMES in improving transient stability of single machine to infinite bus system has already been established by the studies carried out so far. The effect of further increasing $TFC$ on the performance of P-SMES has also been studied. For this purpose $TFC$ is increased from 0.21667 seconds to 0.26668 seconds. The swing curves are plotted, in Fig.3.37 the variations in swing curves indicate that even for $TFC = 0.25001$ seconds system remains stable and it become unstable for $TFC$ equal to 0.26668 sec. It may be seen from the Fig.3.37 that damping of transient swings deteriorates with increasing fault clearing time.
3.9 Performance of P-SMES at different Loading Conditions

Two different loadings have been considered for observing the effectiveness of P-SMES under changing loading conditions. In one case the active power output of the synchronous generator is less than the capacity of P-SMES, whereas in the other case it is higher than that. Following type of loadings have been considered:

Operating condition 1: The synchronous generator is assumed to operate at lower power output with $P = 0.375$ p.u. and $Q = 0.03$ p.u. The fault is cleared at $TFC = 0.21667$ seconds. Fig 3.38 shows the swing curve for this operating condition. The swing curve without any device is also shown in Fig.3.38. It can be seen that significant damping is achieved when P-SMES is used.
Operating condition 2: The synchronous generator is assumed to operate at higher power output with $P = 0.85$ p.u and $Q = 0.03$ p.u. The fault is cleared at $TFC = 0.21667$ seconds. Fig 3.39 shows the swing curve for this operating condition. The swing curve without any device is also shown in Fig.3.39. It can be seen that significant damping is achieved when P-SMES is used.
3.10 Effect of Fault Clearing Time on the SMES Rating

It has been found that the maximum active power requirement of SMES depends on the fault clearing time. With increase in fault clearing time it increases. The variation of the maximum active power requirement of SMES is shown in Table 3.1 and the trend is plotted in Fig.3.40. Performance of SMES is very satisfactory under different operating conditions (for light load as well as heavy load conditions), in case where the fault clearing time is more than the critical fault clearing time under the representative operating conditions considered. It has been found that the requirement of SMES rating increases with increase in $TFC$ accordingly. If a fast acting circuit breaker is used to clear the fault in the system, the requirement of SMES rating for the maintenance of transient stability increases.

![Graph showing performance of SMES with and without SMES](image)

Fig. 3.39 Performance of SMES at $P = 0.85$ pu and $Q = 0.03$ p.u.

3.10 Effect of Fault Clearing Time on the SMES Rating

It has been found that the maximum active power requirement of SMES depends on the fault clearing time. With increase in fault clearing time it increases. The variation of the maximum active power requirement of SMES is shown in Table 3.1 and the trend is plotted in Fig.3.40. Performance of SMES is very satisfactory under different operating conditions (for light load as well as heavy load conditions), in case where the fault clearing time is more than the critical fault clearing time under the representative operating conditions considered. It has been found that the requirement of SMES rating increases with increase in $TFC$ accordingly. If a fast acting circuit breaker is used to clear the fault in the system, the requirement of SMES rating for the maintenance of transient stability increases.
Table 3.1 Variation of the Maximum Active Power Requirement of SMES

<table>
<thead>
<tr>
<th>TFC</th>
<th>$P_{smes}(\text{max})$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0500</td>
<td>.0867</td>
</tr>
<tr>
<td>0.0834</td>
<td>.1993</td>
</tr>
<tr>
<td>0.1334</td>
<td>.3084</td>
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<tr>
<td>0.16667</td>
<td>.3800</td>
</tr>
<tr>
<td>0.20000</td>
<td>.4158</td>
</tr>
<tr>
<td>0.21667</td>
<td>.4522</td>
</tr>
<tr>
<td>0.23334</td>
<td>.4909</td>
</tr>
<tr>
<td>0.25001</td>
<td>.5253</td>
</tr>
<tr>
<td>0.26668</td>
<td>.5631</td>
</tr>
</tbody>
</table>

Fig. 3.40 Variation in $P_{smes}$ vs variation in fault clearing time
3.11 Conclusion

In this chapter the transient stability investigations have been carried out of single machine connected to infinite bus system where SMES devices are used to control stability. Different types of controllers have been tried to control the power from/to the SMES to help to restore the system to a stable condition. A simple system has been considered for investigations. Its governing equations have been established to be used in the investigations. In order to compare the performance of the system in conjunction with SMES using different types of controller a suitable performance index has been documented and used for the purpose. Two representative system variable namely $\Delta \delta$ and $\Delta \omega$ were selected for comparative study and it was found that system variable $\Delta \omega$ may be used as a control signal for the SMES controller to enhance the transient stability of the system under investigation. The practical implementation of the control signal was of the main deciding factor in favour of $\Delta \omega$ as the promising signal for further investigations in this thesis.

In order to investigate the effectiveness of the SMES in damping the oscillations the investigations have been carried out for two cases namely when the fault is cleared at the instant of critical fault clearing time and also for a case when the fault is cleared at a time beyond the critical fault clearing time.

Two types of control schemes i.e. Proportional-SMES and Proportional-Integral-SMES have been tried for the transient stability investigations. It was observed that transients damp out in 3.0 seconds in both the cases. The maximum swing of rotor angle is less in case of Proportional-Integral-SMES as compared to Proportional-SMES. Proportional-SMES being simpler is taken for all further investigations.

To find out the effectiveness of SMES in improving transient stability of a power system, its performance is compared to a conventional dynamic brake presently in use. It is observed that the performance of the system considered with SMES is better than that with optimally switched dynamic brake under similar conditions of operation.
Through investigations it has been observed that variation in the gain coefficient $k_v$ provided for the control of reactive power, there is negligible effect on rotor oscillations. Therefore, change in terminal voltage, as control signal does not have any appreciable effect on transient stability of the system.

It is pertinent to study the effect of increasing the fault clearance time on the performance of P-SMES. Since P-SMES was been selected for subsequent investigations, it is observed that the system is found to be stable for fault clearing time even more than critical fault clearing time. However, the system becomes unstable at $TFC$ equal to 0.26668 seconds. Therefore it can inferred that the transient stability of the system is very much enhanced, when SMES is used to maintain stability even for fault clearing time that is greater than critical fault clearing time. It is well known fact that the capacity of the SMES is an important aspect to be decided on the basis of the investigations; therefore the requirement of SMES power inflow/outflow was studied observed and plotted in the form of suitable curves. The power requirement of SMES was obtained as the fault clearing time was varied. It has been found that the requirement of SMES rating increases with increase in $TFC$ accordingly if a fast circuit breaker is used to clear the fault in the system, the requirement of SMES rating for the maintenance of transient stability decreases.