DYNAMICS AND 8TABILITY OF WIND AMD DIESEL TURBINE GENERATORS WITH SUPERCONDUCTING MAGNETIC ENERGY STORAGE UNIT ON AN ISOLATED POWER SYSTEM

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Abstract - Dynamic system analysis is carried out on an isolated electric power system consisting of a diesel generator and a wind turbine generator. The 150-kW wind turbine is operated in parallel with a diesel generator to serve an average load of 350-kW. A comprehensive digital computer model of the interconnected power system including the diesel and wind power dynamics with superconducting magnetic energy storage <SMES) unit is developed. Time domain solutions are used to study the performance of the power system and control logic. Based on a linear model of the system it is shown that changes in control system settings could be made to improve damping and optimization of gain parameters and stability studies are done using the Lyapunov technique and eigenvalue analysis. The effect of introducing superconducting magnetic energy storage unit for improvement of stability and system dynamic response is studied.

Keywords - Wind and diesel turbine generators, control systems, stability and optimization.

INTRODUCTION

A constantly growing energy demand has to be met through an adequately planned electrical power generation programme. Although electrical energy is environmentally the most benign form of energy, its production is routed through conventional fossil fuel burning or through nuclear energy and wherever possible through hydro resources. All of these in addition to other disadvantages give rise to environmental issues of varied nature. It is therefore necessary to consider the problems of electrical energy generation and environment jointly so that the growing need of electricity for industrialization would be met with minimal environmental degradation. One of the solutions is to utilize wind energy in favourable sites which are remote from centralised energy supply systems. Since wind power varies randomly there must be a stand-by power source to meet load demand. Hind and diesel system is one of the hybrid systems utilizing more than one energy source. A hybrid wind and diesel system is quite reliable because the diesel acts as a cushion to take care of variation in wind speed, and would always provide power equal to load power minus the wind power.

In the paper by Scott, et al [1] the study focuses upon the dynamic interaction investigation for the purpose of quantifying any increased disturbance to the Block Island Power Company (BIPCO), on Block Island (which operates on an isolated electric power system consisting of diesel and wind turbine

generators) resulting from connection of the MOD-OA wind turbine generator. The work described here-in is to provide the capability of simulating the dynamic performance of the wind turbine generator with superconducting magnetic energy storage operated in parallel with a diesel engine generator on an isolated power system. The stability of the system is studied by using the Lyapunov technique and eigenvalue analysis. The system can run in either of the three modes namely:

(i)   Diesel generating set,
(ii) Hind turbine generator with SMES unit,
(iii) Hind and diesel turbine generators with SMES unit.

In the third mode of operation the SMES unit is used to store power during high wind and less load demand. Operation of diesel for extended periods at low power levels (less than 50%) could result in possible engine damage and/or excess oil accumulation in the exhaust stack. Therefore, in case of rapid wind or less load demand the excess energy can be stored in superconducting magnetic energy storage unit. A fast acting energy storage such as superconducting magnetic energy storage can effectively damp electromechanical oscillations in a power system, because it provides storage capacity in addition to kinetic energy of the generator rotor,which can share the sudden changes in power requirement.

Methods are described for the suitable control of the system and optimal values for the gain parameters of the existing power system are determined to extract the maximum benefit out of the available capacity. The paper provides an overview of the general dynamic characteristics of wind and diesel turbine generators with storage unit as an isolated electrical power system and discusses the impact of variation in system design and control. The study concludes that wind turbine generation in addition to being environmentally non-polluting, can be a practical option resulting in power generation in parallel with conventional diesel system, providing a large portion of the power required by an isolated utility.

ANALYSIS

The model considered here consists of the following sub-systems:
(i)   Hind dynamics model,
(ii) Diesel dynamics model,
(iii) Superconducting magnetic energy storage unit,
(iv) Blade pitch control of wind turbine,
(v)   Generator dynamics model.

The wind model is one feature that is unique to the wind turbine generator and is not required for diesel generator system in the stability programme. A model which is presented by Anderson, et al [2] can properly simulate the effect of wind behavior, including gusting, rapid (ramp) changes and background noise. The basic condition for start up and synchronization is that the wind speed is to be within acceptable range and there must be a phase match between the generator voltage and system voltage [1].

The diesel dynamics is associated with diesel power and the nature of the dynamic behavior in this model is dominated by the diesel speed governor controller. A total power set point is selected in

which it can be manually adjusted from zero to maximum value. This power set point will .also take into account the capacity of SMES unit. The purpose of the adjustable power set point is to allow system ·utility personnel to lower the power setting than the maximum settings of the wind generator to prevent controlling diesel from dropping to less than 50% rated power. Operation of diesel for extended periods at low power levels could result in possible engine damage. During high wind speed and less load demand the excess energy will be stored in the magnets with superconductive windings of SMES unit. Such superconducting magnetic energy storage systems would consist of a superconducting inductor, a helium refrigerator and dewar system to keep the temperature well below the critical temperature for the superconductor, and an ac/dc converter. Charging and discharging is achieved by varying the dc voltage, applied to the inductor, through a wide range of positive and negative values. This can be achieved by controlling the delay angle of commutation. Detailed descriptions of SMES unit and its various design features can be found in [3,4,5]. Application of SMES for enhancing the utilization of photovoltaic power generation has also been proposed [6]. Though the SMES technology is new and currently quiet expensive, it is a fast developing one and holds high promise. The intensive search for high temperature superconducting materials gives further impetus for studying the applications of this technology.

Pitch control has the potential for producing the highest level of interaction because of the presence of both diesel and wind turbine control loops. When wind power rises above the power set point and SMES unit is fully charged, the pitch control system begins operating to maintain an average power equal to the set point. The pitch control system consists of a power measurement transducer, a manual power set point control, a proportional plus integral feedback function, and a hydraulic actuator which varies the pitch of the blades. Turbine blade pitch control has a significant impact on dynamic behavior of the system. This type of control only exists in horizontal axis machines. Variable pitch turbines operate efficiently over a wider range of wind speeds than fixed pitch machines. However cost and complexity are higher.

Generator dynamics model consists of a synchronous generator driven by a diesel engine through a flywheel and connected in parallel with an induction generator driven by a wind turbine. The diesel generator will act as a dummy grid for the wind generator which is connected in parallel. Variations of electrical power due to changes in wind speed should be as small as possible, this is obtained by using induction generator as a wind turbine drive train. Unlike synchronous generators, induction generators are high compliance couplings between the machine and the electrical system. This is true for induction generators with slip of at least 1-2% at rated power [7,8]. The controlled variables are turbine speed and shaft torque. Control acts on the turbine blade angle (pitch control), since the torque-speed characteristic of the induction generator is nearly linear in the operating region, torque changes are reflected as speed changes. Therefore, it is possible to provide a single speed controller to control speed as well as torque.

CONFIGURATION OP THE SYSTEM

Figure 1 shows the basic configuration of a wind and diesel turbine generation system with a SMES unit.

Figure 2 shows the basic configuration of a SMES unit in the power system. When wind power rises above the power set point, the superconducting coil can be charged to a set value (less than the full charge) from the wind turbine generator during normal operation of the system. The DC magnetic coil is connected to the wind turbine generator through a power conversion system which includes an inverter/converter. Once the superconducting coil gets charged, it will conduct current, which supports an electromagnetic field, with virtually no losses. A helium refrigerator and dewar system is used to keep the temperature well below the critical temperature for the superconductor [3,4].
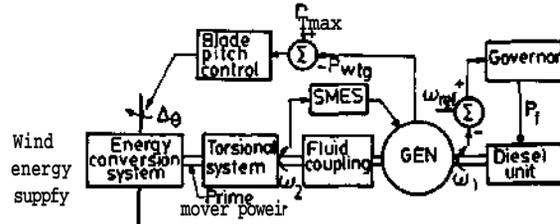

Fig. 1 Basic configuration of a wind and diesel turbine generators with SMES unit

When there is a sudden rise in the demand of load, the stored energy is immediately released through power system . As the governor and pitch control mechanisms start working to set the power system to the new equilibrium condition, the coil charges back to its initial value of current. Similar is the action during sudden release of the loads. The coil immediately gets charged towards its full value, thus absorbing some portion of the excess energy in the system, and as the system returns to its steady state, the excess energy absorbed is released and the coil current attains its normal value. For protection of the equipment a path for the inductor current must always be provided in case of faults such as disconnection of the converter transformer or else. This is done by connecting two bypass SCRs as shown in Fig. 2. In case of internal trouble (inside the dewar), conceivably it might be desirable to dump energy externally. The resistor R in Fig. 2 is intended to serve such purpose.
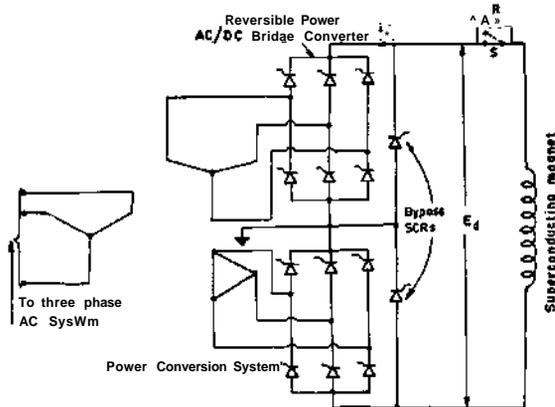

Fig. 2 Configuration of SMES unit in the power system

WIND AND DIESEL TURBINES MATHEMATICAL MODEL WITH SMES

A digital computer model for wind and diesel system with SMES unit is shown in Fig. 3. The system is a linear continuous-time dynamic system and it can be represented by a set of linear differential equations of the form:

$$\dot{X} = [A]\,X + [B]\,U + [\Gamma]\,£ \tag{1}$$

where $\underline{X}$, $\underline{U}$ and $\underline{P}$ are state, control and disturbance vectors and [A], [B] and [V] are constant matrices associated with them respectively. However, if $\underline{P}$ represents the load disturbance and since the control is expressed in terms of state variables/disturbance, equation (1) can be conveniently brought to the modified form:

$$\dot{\underline{X}}(t) = [A]\ \underline{X}(t) + [I^1]\ \underline{P}(t) \qquad (2)$$

$$\underline{X}(0) = -\ \underline{X}_{ss} \text{ and } \underline{X}(\infty) = \underline{0} \qquad (3)$$

where $\underline{X}_s$ is the steady state value of the modified state vector and $\underline{X}(0)$ is the vector of initial conditions. The time domain solution of equation (2) at a particular time t » T can be obtained as:

$$\underline{X}(T) = {}_e{}^{[A1T}\ \underline{X}(0)) + e^{[A1T} \int_0^T e^{1A)T}\ [V]\ \underline{P}(T)\ dT \qquad (4)$$
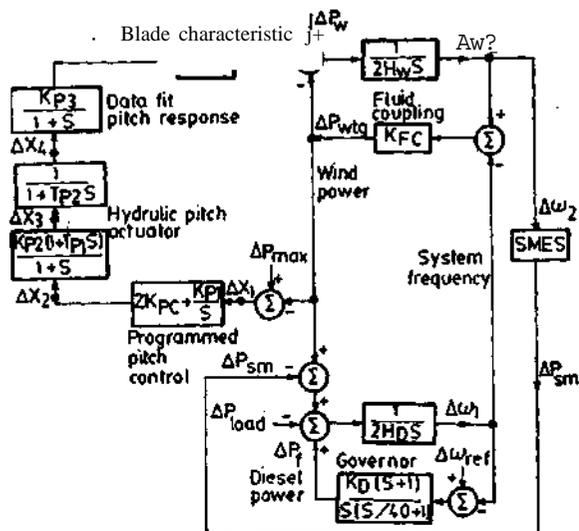

Fig. 3 Functional block diagram for wind and diesel turbines with pitch control and SMES unit

Wind and Diesel System without SMES Unit

For the system without SMES unit $\underline{X}$ and $\underline{P}$ are 9th order state and disturbance vectors obtained as:

$$\underline{X} = [\Delta\omega_2\ \Delta\omega_1\ \Delta P_{f_1}\ \Delta P_{f'}\ \Delta X_1\ \Delta X_2\ \Delta X_3\ \Delta X_4\ ] \qquad (5)$$

$$\underline{P} = [0\ \Delta P_{load}\ 0\ 0\ 0\ 0\ 0\ 0\ 0] \qquad (6)$$

where ΔP_{f_1} is a dummy variable obtained by splitting the block for diesel governor. Other state variables are marked in Fig. 3.

Hind and Diesel System with SMES Unit

By adding SMES unit to the system $\underline{X}$ and $\underline{P}$ are 11th order state and disturbance vectors obtained as:

$$\underline{X} = [\Delta\omega_2\ \Delta\omega_1\ \Delta P_{f_1}\ \Delta P_f\ \Delta X_1\ \Delta X_2\ \Delta X_3\ \Delta X_4\ \Delta P_m$$
$$\Delta E_d\ \Delta I_d] \qquad (7)$$

$$\underline{P} = [0\ \Delta P_{load}\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0\ 0] \qquad (8)$$

where ΔE_d is the voltage deviation of SMES unit and

ΔI_d is the current deviation of SMES unit. Other state variables are marked in Fig. 3.

CONTROL OP SMES UNIT

Control of the delay angle of commutation, a, provides the means for varying continuously the bridge voltage E_d throughout a wide range of plus and minus values. The operation of SMES unit, that is, charging, discharging, the steady state mode and the power modulation during dynamic oscillatory period is controlled by the application of the proper positive or negative voltage to the inductor. If losses are assumed negligible, the dc voltage is given by [3,9]:

$$E_d = 2\ V_{do}\ \cos a - 2I_d\ .R_c \qquad (9)$$

where E_d = dc voltage applied to the inductor, kv
V_{do} = maximum open circuit bridge voltage of each 6-pulse converter at $a=0°$, kv
a = firing angle, degree
I_d = current through the inductor, kA
R_c = equivalent commutating resistance, ohm

The inductor is initially charged to its rated current, I_{do} by applying a small positive voltage. Once the current has attained the rated value, it is held constant by reducing voltage ideally to zero. Since the coil is superconducting, a very small voltage may be required to overcome the commutating resistance. The energy stored at any instant is.

$$W_L = \frac{LI_d^2}{2} \qquad MJ \qquad (10)$$

where L = inductance of SMES system, H

Once the rated current in the inductor is reached, the unit is ready to be coupled with the power system for load-frequency control application. The wind frequency deviation $\Delta\omega_2$ of the power system is sensed and used to control the SMES voltage, E_d. During sudden loading in the system the frequency will fall and SMES gets discharged. The control voltage E_d, is to be negative since current through the inductor and the thyristors can not change its direction. The incremental change in the voltage applied to the inductor is expressed as:

$$\Delta E_d = [\frac{K_o}{1+ST_{dc}}]\ \Delta\omega_2 \qquad (11)$$

where ΔE_d « the incremental change in converter voltage, kv
T_{dc} = converter time delay, sec.
K_o = the gain of the control loop, kV/Hz
S = the Laplace operator, d/dt

The incremental change in the current applied to the inductor is,

$$\Delta I_d = -\frac{1}{SL}\ \Delta E_d \qquad (12)$$

Power into the inductor at any time, $P_d = E_d\ .\ I_d$ and initial power flow into the coil is $P_{do} = E_{do}\ .\ I_{do}$ where E_{do}, I_{do} are the magnitudes of voltage and current prior to the load disturbance. In the response to the load disturbance the power flow into the coil can be expressed as:

$$P_d = (E_{do} + \Delta E_d)(I_{do} + \Delta I_d) \qquad (13)$$

Thus the incremental change in power flow per unit is given by:

$$\Delta P_d = (I_{do}\ \Delta E_d + \Delta E_d\ \Delta I_d)/\ P_R \qquad p.u. \qquad (14)$$

where P_R = rated area capacity, kW

INDUCTOR CURRENT DEVIATION FEEDBACK

The SMES unit has a natural tendency of current restoration which is a very slow process and artificial enhancement of rate of restoration is required. Use of inductor current deviation feedback in the SMES control loop is suggested here. The inductor current deviation can be sensed and used as a negative feedback signal in the SMES control loop to achieve quick restoration of current. Then, with frequency deviation as control signal,

$$\Delta E_d = \frac{1}{1+ST_{dc}} [K_o \Delta\omega_2 - KI_d \Delta I_d]$$ (15)

where K_{Id} is the gain corresponding to the ΔI_d feedback, kV/kA. The block diagram representation of such a control scheme is shown in Fig. 4.
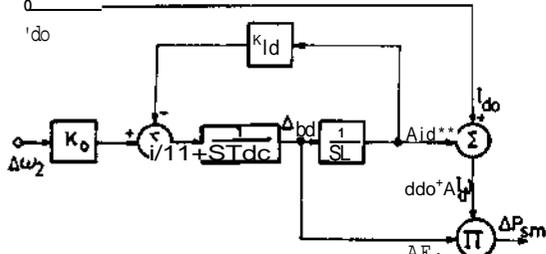

Fig.4 Block diagram representation of the SMES control with inductor current deviation feedback

PARAMETER OPTIMIZATION BY LYAPUNOV STABILITY THEOREM

The gain parameters are to be set to the optimal values ensuring system stability. The Lyapunov second method for linear systems is used here for optimization that guarantees stability [10,11]. The performance of a linearised dynamical system for all disturbances can be described by a set of first-order differential equations expressed in terms of the state variables, $(X_1, X_2, ---, X_n)$ as follows:

$$\hat{\underline{X}}(t) = [\hat{A}] \hat{\underline{X}}(t)$$ (16)

Therefore, for wind and diesel system with SMES unit in an autonomous form $\hat{\underline{X}}$ is a 11th order state vector as:

$$\hat{\underline{X}} = [\Delta\omega_2 \quad \Delta\omega_1 \quad (\Delta P_{f_1} - \Delta P_{load}) \quad (\Delta P_f - \Delta P_{load}) \quad \Delta X_1$$
$$\Delta X_2 \quad \Delta X_3 \quad \Delta X_4 \quad \Delta P_{-1} \quad \Delta E_d \quad \Delta I_d]$$ (17)

The performance index (objective function) to be minimized is:

$$\eta = \int_0^\infty \hat{\underline{X}}'(t) [Q] \hat{\underline{X}}(t) \, dt$$ (18)

where [Q] is positive definite weighting matrix. Minimization of η leads to the minimum value of the sum of weighted square error. η is minimized with respect to the chosen parameters.

$$\eta = [\hat{\underline{x}}(o)]' [P] [\hat{\underline{x}}(0)]$$ (19)

where [P] is a positive definite Hermittian matrix obtained from the solution of:

$$[\hat{A}]' [P] + [P] [\hat{A}] = - [Q]$$ (20)

Equation (20) is solved for [P] using the iterative technique described in [12]. The convergence of the solution for equation (20) ensures that all the eigenvalues of $[\hat{A}]$ have negative real parts, assuring stability. The process for evaluating η is repeated by varying one parameter at a time, keeping the other parameters constant in the $[\hat{A}]$ matrix. Optimal values are those corresponding to the minimum value of the performance index.

The system data given in Appendix. Fig. 5 shows the performance index curve with and without SMES unit connected to the system. Here gain ZK_{PC} is to be optimized. Weights are associated with frequency deviations and pitch control power deviation. The optimum value of the ZK_{PC} gain for wind and diesel system, a) without SMES unit and b) with SMES unit are obtained which are 1.8 and 2.0 respectively. The stability with the optimal gains thus obtained is ensured by checking the convergence of equation (20).
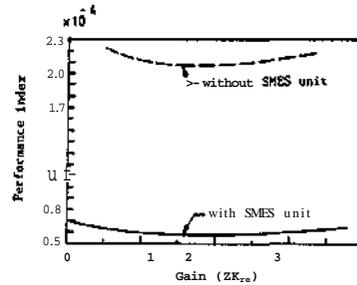

Fig. 5 Performance index with and without SMES unit

ANALYSIS OF SYSTEM STABILITY USINO THE EIGENVALUE SENSITIVITY TECHNIQUE

The dynamic stability of wind and diesel turbine generators was investigated by obtaining eigenvalues of the system with variation in the electrical system load and SMES unit parameters. Equation (1) can be conveniently brought to the form:

$$\hat{\underline{X}}(t) = [\hat{A}] \hat{\underline{X}}(t)$$ (21)

The eigenvalues of $[\hat{A}]$ matrix are the roots of characteristic equation [11].

$$| X[I] - [\hat{A}]| = 0$$ (22)

where [I] is an identity matrix of the same order , as that of $[\hat{A}]$

λ s are the eigenvalues of the matrix [&]

Eigenvalues of wind and diesel system with and without SMES unit have been studied. It can be seen that for the given SMES unit system parameters ($K_0 = 6000$ kV/Hz, $I_{do} = 2$ kA, L=10 H, $K_{Id} = 5$ kV/kA) two more eigenvalues are added to the one without SMES unit. All the eigenvalues are in the left half of the S-plane because of which the system is stable. It is shown in Fig. 6(a) that the system stability and damping are largely improved by adding SMES unit to the system. Some of the eigenvalues which are far from the imaginary axis are ignored, as these eigenvalues do not have much impact on the system. The real axis eigenvalue close to origin moves away from the origin by a considerable distance (i.e. from -0.00550 to -0.00701), this movement results in improvement of the stability margin. It is further seen that the stability margin increases with increase in SMES gain parameter K_{Id}, keeping all other parameters fixed. By increasing I_{do} from 1 kA to 5.5 kA and keeping all other parameters fixed the complex eigenvalues move further away from the imaginary axis, thus improving the damping, and the real axis eigenvalue moves slightly away from the origin which improves the stability as shown in Fig. 6(b). By increasing K_{Id}

from 1 kV/kA to 10 kV/kA and keeping other parameters fixed it is seen that the system stability improves.
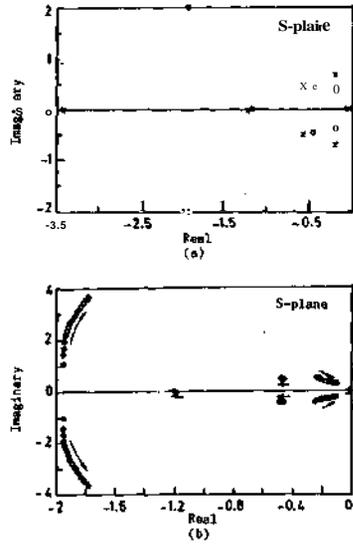
o with SMES unit   X without SMES unit

Fig. 6 Eigenvalue location with SMES unit parameters
(K_0=6000 kV/Hz, I_{do}=2 kA, L=10 H, K_{Id}=5 kV/kA)

TRANSIENT RESPONSES

Transient Responses with and without SMES Unit

The transient responses for frequency and power deviations of the wind and diesel system with and without SMES unit are shown in Fig. 7 for a step load increase of 0.01 p.u.. It shows that addition of SMES unit has a considerable effect on the amplitude of oscillations.
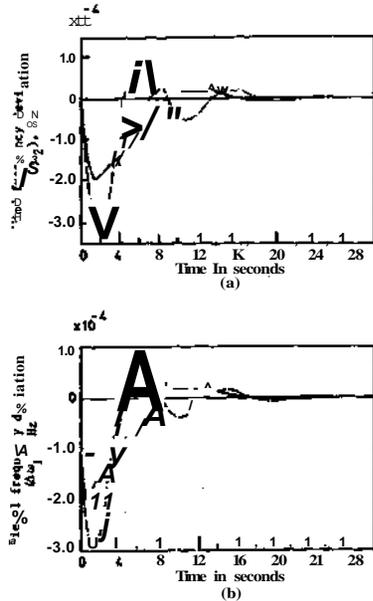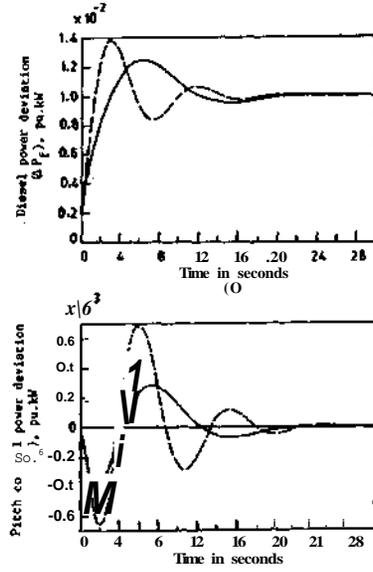

Fig. 7(a,b) Frequency response with and without
SMES unit

——• with SMES unit———————without SMES unit

Fig. 7(c,d) Power response with and without SMES unit

Figure 7 reveals improvement of the system frequency oscillations and power deviations for the system with SMES unit. Settling time is nearly the same for both cases around 24 seconds, with their respective optimized integrator gains. It can be observed that with the addition of SMES unit, the frequency and power deviations reduce by about 30 %.

Transient Responses with Variation of SMES Unit Parameters

The important parameters of the SMES unit are the gain parameter K , the initial inductor current $I^$, the inductance £ and the gain of inductor current deviation feedback K_{Id}.
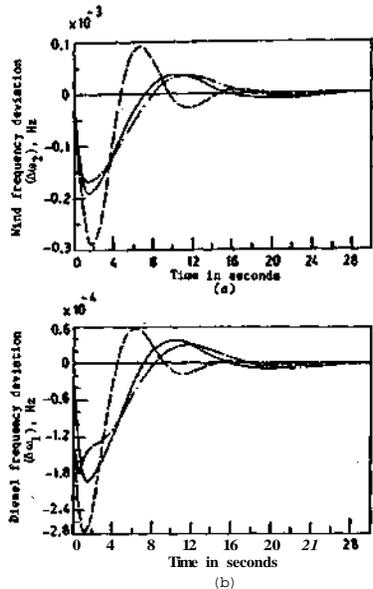

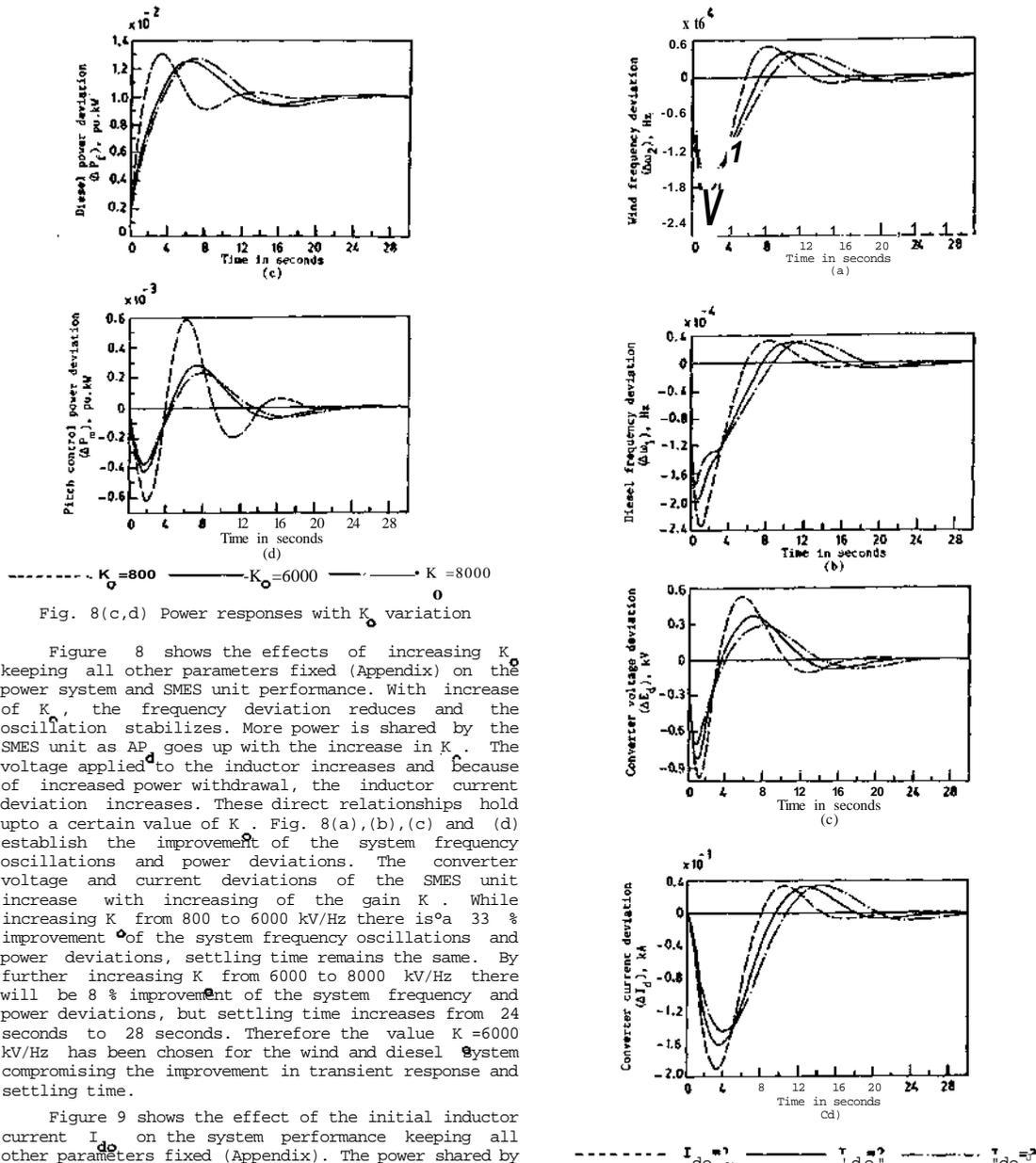Fig. 8(a,b) Frequency responses with K_0 variation

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Fig. 8(c,d) Power responses with K_o variation

Figure 8 shows the effects of increasing K_o keeping all other parameters fixed (Appendix) on the power system and SMES unit performance. With increase of K_o, the frequency deviation reduces and the oscillation stabilizes. More power is shared by the SMES unit as ΔP_d goes up with the increase in K_o. The voltage applied to the inductor increases and because of increased power withdrawal, the inductor current deviation increases. These direct relationships hold upto a certain value of K_o. Fig. 8(a),(b),(c) and (d) establish the improvement of the system frequency oscillations and power deviations. The converter voltage and current deviations of the SMES unit increase with increasing of the gain K_o. While increasing K_o from 800 to 6000 kV/Hz there is a 33 % improvement of the system frequency oscillations and power deviations, settling time remains the same. By further increasing K_o from 6000 to 8000 kV/Hz there will be 8 % improvement of the system frequency and power deviations, but settling time increases from 24 seconds to 28 seconds. Therefore the value K_o=6000 kV/Hz has been chosen for the wind and diesel system compromising the improvement in transient response and settling time.

Figure 9 shows the effect of the initial inductor current I_{do} on the system performance keeping all other parameters fixed (Appendix). The power shared by the inductor goes up with the increase in the initial inductor current and the system performance improves greatly. The values of I_{do} chosen are 1, 2 and 3 kA. Increase of I_{do} from 1 to 2 kA will result in 20 % improvement of the system response. The frequency oscillations are shown in Fig. 9 (a) and (b). By increasing I_{do} the SMES converter voltage and current deviations are reduced as seen in Fig. 9 (c) and (d), similarly the power deviations are reduced similar to the case with increasing K_o. Further increasing I_{do} from 2 to 3 kA will bring 20 % improvement of the system response. The value I_{do}=2 kA is selected as in SMES unit a higher value of I_{do} amounts to a higher heat loss.

From figs. 9 (c) and (d) the SMES power can be computed as a function of time by multiplication of the inductor voltage and current. The maximum value of

Fig. 9 Transient responses with I_{do} variation

power thus obtained, with a safety factor, may be chosen as the power rating of the SMES and the converter unit. For the particular system considered, the power rating obtained is 250 kW. Furthermore, any change in converter output voltage is accompanied by a corresponding change in reactive power interaction between the AC system and SMES unit. In order to minimize these reactive power fluctuations, operation of the 12 pulse converter in buck-boost mode of control has been proposed in [4,13].

The effects of the choice of inductance on the power system performance is then studied. The inductance L determines the energy stored in the inductor. Ideally the SMES inductance value does not

significantly influence its rate of energy transfer and an increase in inductance would only reduce the SMES current deviation following a disturbance. Value of L is chosen according to the minimum amount of energy storage required in a system to obtain the necessary damping. However, the practical considerations, such as the maximum permissible rates of change of voltage and current across the converter's thyristor elements and the limiting speed with which firing angles can be changed, are to be given due weightage while choosing the inductance value. Further, too small an inductance value will make the inductor current change too quickly and the unit will hit the limit and stop operating soon.

CONCLUSIONS

A comprehensive mathematical model has been developed for wind and diesel turbine generators operating on an isolated electric power system. The use of a superconducting magnetic energy storage unit for load leveling/damping purpose is presented in the paper. The simulation incorporates wind turbine pitch control and diesel governor. The dynamics and transient stability of the system with and without SMES unit is studied and the transient responses for frequency oscillations and power deviations are compared. The effectiveness of an SHES unit in damping out these oscillations and in quickly restoring the system states to a new equilibrium state has been established. The study has further shown improvement in transient response with variation of SHES unit parameters. Optimization of gain parameters is done by the second method of Lyapunov, which ensures system stability. Analysis of stability has been further explored using eigenvalue sensitivity technique. The eigenvalues of the system with and without SMES unit have been studied and effect of variation of SMES unit parameters on eigenvalue locations are plotted.

APPENDIX

SYSTEM DATA

Area capacity, P_R = 350 kW

H_W = inertia constant on machine base = 3.5 for wind system.

H_D = inertia constant on machine base = 8.5 for diesel system.

K_F = 16.2 Hz/pu.kW K_D = 16.5 Hz/pu.kW

K_1 = 4.0 T_{P1} = 0.06 s

K_2 = 1.25 T_{P2} = 0.041 s

K_3 = 1.4 K_{Pc} = 0.08

Δ load = 0.01 pu.kW A_{W} = 0.0 pu.kW

SMES UNIT DATA

I_{do} = 2.0 kA L = 10.0 H

K_O = 6000 kV/Hz K_{Id} = 5.0 kV/kA

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