International Journal of Computing and Digital Systems
ISSN (2210-142X)
Int. J. Com. Dig. Sys. 10, No.1 (Nov-2021)

http://dx.doi.org/10.12785/ijcds/1001110

Use of Super Conductor Magnetic Energy Storage System and FACTS Devices for Two-Area Load Frequency Control Having Synchronous Generators and DFIG Wind Generators

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Received 10 October.2020, Revised 1 April. 2021, Accepted 10 April. 2021, Published 25 Nov. 2021

Abstract: The load change in a synchronous generator (SG) based power generation system is common which will mainly influence the change in voltage, power flows, frequency, load angle and burden of transmission lines and transformers due to change in current flow. The study which analyses the behavior of load change, compensating devices and its impact on change in frequency and real power flow is termed as load frequency control. The generators like Doubly Fed Induction Generator (DFIG), SG are supplying power in one area, and a total of two areas are considered in this paper. The load change is done in area-1 only and a change in frequency is observed in both areas. Two cases, one with thyristor-based controller capacitor storage phase shifters (TCPS) and the other with a superconducting magnetic storage system and hybrid models of such are done and in another case, Flexible AC Transmission devices such as TCPS, SSSC, UPFC and IPFC are used. Earlier authors have shown that compared to battery and ultra-capacitors, superconductor magnetic energy storage system (SMES) plays a vital role and few authors observed frequency regulation with different FACTS devices. Hence, we extended with SMES and FACTS devices and also in a coordinated manner to observe which combination gives better performance for the same disturbance. Using MATLAB software, the frequency change is observed in both cases, in the first case, TCPS is found better and in the second case, IPFC is found better in compensating the frequency change.

Keywords: Doubly Fed Induction Generator (DFIG), Wind Energy, Load Frequency Control, FACTS Devices, Superconducting Magnetic Energy Storage System (SMES).

1. Introduction

The power system main components are generating stations, transmission lines, distribution lines, load centres and industrial and sub-station load management units. The generating stations play a key role in supplying load reliably and effectively to the load centres without voltage or frequency disturbance. The distribution and transmitting stations supply real power at desired voltage and frequency to industrial, commercial and domestic loads such that the deviation in voltage and frequency with respect to rated value to be as lesser as possible. If there is a deviation in voltage or frequency due to load disturbances, the performance and the life of motors and lighting loads deteriorate. To overcome this, the distribution, transmission and generating stations control the frequency such that the deviation in frequency is as low as possible last few decades [1, 2].

The load frequency control is done on the distributed generation model is done for low and medium power level applications where generator speed control and model-based control techniques are widely used [3-6]. There are various advanced control schemes such as adaptive reference models, intelligent fuzzy, neural networks, and meta-heuristic techniques like GA, PSO etc., are used [7-

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10]. These advanced controllers are very quick and can predict the load changes and can adapt to the system behavior as per the requirements. Other than controllers, compensating devices like energy storage and FACTS devices are crucial for system performance and stability improvement [11-18]. These devices will supply or absorb real or reactive power to the load system were installed to meet the change in the demand. Mostly, batteries, fuel-cell, capacitors are used to supply real power when loading increases and absorb when the load decreases. The inverter which connects these dc supply energy sources to ac grid will control reactive power flow. The FACTS devices are controlled voltage and current control switches like IGBTs, SCRs. The FACTS devices include thyristor controlled capacitor storage phase shifters (TCPS), STATCOM, SSSC, IPFC, UPFC, and SVC are used for reactive power flow, frequency, voltage, load angle and compensation.

The effect of penetration of wind turbines will largely influence the area generation control (AGC), primarily the frequency output and the wind generator and overall system stability [19]. This is due to the fact that the inverter-based generator will have poor inertia and has a considerable impact of regaining to its original state after a small disturbance. The AGC control plays a vital role in improving overall stability and performance under turbulences. For this, in [20], the authors used a new Jaya algorithm to improve the AGC and frequency control in a multi-area power system. The frequency restoration will be more complicated for a multi-inverter grid-connected system, and hence a better control device technique is required to improve stability as well as economic operation effectively [21]. So authors used distributed hierarchical control strategy and found it better than the conventional scheme. Beyond new control strategies, energy storage devices also play a crucial role in frequency restoration and performance enhancement. To prove this, the authors of the paper [22] used two mass DFIG with flywheel energy storage systems and they found the results are very satisfactory. In addition to this, many authors various available energy storage devices to improve the frequency, power, and generation deviation due to load or grid or any source-side variations and found their devices also will influence the system behaviour considerably [23, 24, and 25]. SMES, TCP, SSSC are used for AGC and frequency regulation and found the improvement in frequency error regulation is better and found best when coordinated two or more combination storage. However, the compensation is very accurate and effective, but also is cost-effective. In [24 and 25], the authors used adaptive fuzzy PID to show their work effectiveness for the analysis like frequency regulation and real power flow control.

A new LFC control is done by the recent works by the authors and found their works are also very effective in primary and secondary frequency regulation. The authors in [26] used adaptive neural network controller and [27] with model-based analysis. The primary frequency control for wind farms is observed in [28 and 29], secondary control with [30] and a review paper discussing all the three frequency controllers like primary, secondary and tertiary in their review paper [31].

There are three hierarchical frequency controls, namely, primary, secondary and tertiary controls [19-21]. The governor action for the generator-turbine that is responsible for fuel input and thereby frequency control is called primary frequency control. This will maintain the generator station side overall frequency stability, balancing power between the power station and load centres. The control level with Automatic Generation Control (AGC) is for two or more areas in a large power system, which is said to be a secondary level of frequency control. The frequency level control between the main grid and the micro-grid is said to be tertiary control. The knowledge on all these levels of control helps in effective design control of LFC [16]. The natural frequency response in a power system refers to the combined effect on generators and AGC's [6].

In a large grid-tied system, the frequency fluctuations are lightly affected on the overall power flow and the power quality, but weak grid circuits, these frequency and power fluctuations are considerable and power quality and real power along with frequency oscillations are therefore must be eliminated strictly to the best possible way. Hence, the frequency regulation in a weak grid system is more challenging than in large grids [29, 30]. For the same reason, with increasing utilization of inertia-less types of generation in power grids, it becomes essential for DFIG, TCPS, SSSC, IPFC, SSSC and SMES to participate in primary or secondary or tertiary or all the three frequency regulation modes of operation.

In the light of the above, this paper implements the DE-based optimal tuning of conventional I/PI/PID controllers for LFC of multi-source hydrothermal power systems with and without wind power penetration. Additionally, the effect of TCPS and SMES on the LFC performance is also investigated with the parameters of TCPS and SMES being tuned using the DE algorithm. The system has also been investigated for the weak grid condition to establish the effectiveness of the proposed approach for wide variations in system operating conditions. Besides, the sensitivity analysis has also been carried out for robustness study under wide variations in loading pattern and system parameters. Simulations results are presented to show the effectiveness of the implemented algorithm under different operating conditions.

In this paper, two cases are discussed with the first case, load variation in the area-1 only with frequency compensation, one with SMES, the other with only TCPS and also a hybrid of these SMES and TCPS. In the other case, TCPS, SSSC, UPFC and IPFC devices are used and the frequency compensation is discussed. To find the better device among these in terms of frequency compensation, the complexity of control and price are done. The second section discusses the area control error in a two-area system mathematically, the third section discusses the DFIG wind-turbine system performance based on the load frequency concept. The fourth section discusses test bed under study and also the design of these energy and FACTS devices and later in the fifth section observes the results and analyzes behavior during sudden load change. Finally, conclusions and major findings of the work are described.

2. Mathematical Modelling of the Two Area System Control Error

The modification in the frequency because of load variation for a two-area system is discussed in this section. The two areas are depicted with suffix A and B for easy understanding and the frequency control is as below. The composite frequency response (β_s) are defined in terms of system governor droop function in Rs-Hz/ per unit (p.u.) power and characteristic load damping (Ds) in p.u. power/ Hz as [12]. Equation (1) helps to understand the frequency regulation in a multiple area power system. The natural response of frequency restrains the variation in the frequency due to generation-load disparity, which requires effective control. The steady-state frequency deviation in pu frequency (Δf) under active power imbalance (ΔP_L) in pu power is defined as (2). The expression (2) refers to the primary level of frequency control. The AGC frequency level control is a secondary or supplementary control that depends on two areas of frequency control which restores tie-line system frequency to its supposed values. This control level plays a vital role in controlling all the area's active power and frequency parameters and hence balances generation-load error which is called as area control error (ACE), in MW. The interconnected tie-line bias control (TBC) [7, 8] helps in regulating and balancing all the areas frequency independently. The ACE is computed in terms of actual (Ta) and scheduled (Ts) exchange power of the line and actual (f) and nominal (f0) system frequency based on balancing area frequency bias (B) according to (3) [16].

$$\beta_s = \frac{1}{R_s} + D_s \tag{1}$$

$$\Delta f = -\frac{\Delta P_L}{\beta_s} \tag{2}$$

$$ACE = (T_a - T_s) - 10 \times B \times (f - f_o) \tag{3}$$

Where, B is a negative value in terms of MW/0.1Hz. It is set to match the "balancing area's frequency response coefficient, and must not be less than 1% of balancing area's estimated yearly peak demand per 0.1Hz change" [9]. For two areas, A and B, the ACE in each area is stated as (4) and (5). Without loss of generality, under the assumption that all the line power terms of the two areas are zero, given by T_{Aa}- T_{As} = - (T_{Ba} - T_{Bs}). This helps to find the frequency deviation using (4) and (5), which is obtained as (6).

$$ACE_A = (T_{Aa} - T_{As}) - 10 \times B_A \times (f - f_o) \tag{4}$$

$$ACE_B = (T_{Ba} - T_{Bs}) - 10 \times B_B \times (f - f_o) \tag{5}$$

$$f - f_0 = \frac{ACE_A + ACE_B}{-10(B_A + B_B)} \tag{6}$$

Equation (6) describes the variation in the system frequency (f-f$_o$) is directly proportional to all individual ACEs vector sum. Now the ACE is derived under the TBC scheme in terms of power imbalance and individual areas composite frequency response is articulated as:

$$\left.\begin{aligned} ACE_A &= (T_a - T_s) - 10 \times B_A \times (f - f_o) \\ &= (-\Delta P_L + \Delta P_{GA} - \Delta P_{LA} - 10 \times B_A \times (f - f_o)) \\ &= (-\Delta P_L - \beta_A \Delta f) - 10 \times B_A \times \Delta f \\ &= -\Delta P_L - (\beta_A + 10 \times B_A) \times \Delta f \end{aligned}\right\} \tag{7a}$$

Further change in generation and load in area-A (ΔP_{GA}, ΔP_{LA}) as,

$$\left.\begin{aligned} \Delta P_{GA} &= -\frac{1}{R_A}\Delta f \\ \Delta P_{LA} &= D_A \Delta f \end{aligned}\right\} \tag{7b}$$

The area control error depended mainly on the frequency deviation, variation in the load, frequency control constants etc., which can be expressed analytically as in equation (7a). The generation and load deviation can be represented in terms of frequency deviation due to load or source or grid side disturbance is described in equation (7b). The definition of steady-state frequency deviation $\Delta f = -\Delta P_L / \beta_S$ is used for ACE for both areas and solving for individual ACE using the above equations

$$ACE_A = \left(\frac{\beta_A + 10B_A}{\beta_s} - 1\right)\Delta P_L \tag{8a}$$

and

$$ACE_B = \frac{\beta_B + 10B_B}{\beta_s}\Delta P_L \tag{8b}$$

where, $B_A = \beta_A = \frac{1}{R_A} + D_A$,

$$\beta_s = \beta_A + \beta_B = \frac{1}{R_A} + \frac{1}{R_B} + D_A + D_B$$

$$B_B = \beta_B = \frac{1}{R_B} + D_B$$

Based on the explanation given for equation (3) and (4) and reference number [9], -10 $B_A = \beta_A$, -10 $B_B = \beta_B$, we get $ACE_A = -\Delta P_L$ and $ACE_B = 0$. It means for the control of frequency in one area, i.e., AGC or ACE in area-A will react to its own disparity in power to meet the frequency response of the system, where ACE in Area-B do not react, but will be a part in the governor and load frequency control response.

3. The DFIG Wind Turbine Modelling Based on Load Data

A. DFIG Modelling based on Load Data

In this section, the deviation in the source to load real power change for the Doubly Fed Induction generation (DFIG) is discussed. The electromagnetic torque (EMT-T_e) developed by the DFIG in terms of the moment of inertia is J, ω_r is rotor speed, B is friction coefficient, T_l is load torque [22].

$$T_e = J\frac{d\omega_r}{dt} + B\omega_r + T_l = \left(Js + B\right)\omega_r + T_l \quad (9)$$

If multiplying with ω_{error} on both sides of equations to get the power parameters of DFIG is articulated as a function of rotor angular speed (ω_r), speed error between reference to actual (ω_{error}) as

$$T_e\omega_{error} = (Js + B)\omega_r\omega_{error} + T_l\omega_{error} \quad (10)$$

We know that the product of speed and EMT is active power. Simplifying the equation (10) for reference stator power (P_s^*) in terms of the generator constants, we get the equation (11a). Now manipulating the power terms in equation (11a) like stator output optimal reference power to load power (P_l) on to the left-hand side and speed coefficient terms to the right-hand side, we get equation (11b). The equation (11b) describes the change in source power to load power and its effect on the change in turbine rotor speed (ω_{error}).

$$P_s^* = (K_{in}s + K_{pn})\omega_{error} + P_l \quad (11a)$$

$$P_s^* - P_l = (K_{in}s + K_{pn})\omega_{error} \quad (11b)$$

where, $K_{in} = J \times \omega_r$ and $K_{pn} = B \times \omega_r$

B. Wind Turbine Modelling in a Two Area Generation Control

The electrical power output from the wind turbine-generator set is governed by the conversion of the turbine's wind kinetic energy into mechanical energy and more the electrical energy generation using a generator. From the basic equations of wind energy conversion system (WECS), output turbine mechanical power (P_{mech}) is given in [14], [20], [22]. Here, the wind power coefficient (C_p), wind speed (υ_ω), the radius of the wind turbine blade (R) and specific density of air (ρ). The C_p depends on tip speed ratio (λ) which is a ratio of blade tip speed and actual wind speed and pitch angle (β) [16], [22].

$$P_{mech} = \frac{1}{2}C_p(\lambda,\beta)\rho A\upsilon_\omega^3 \quad (12)$$

$$C_p(\lambda,\beta) = 0.645[0.00912\lambda + k_1] \quad (13)$$

$$k_1 = \frac{116\lambda_t - 5 - 0.4(2.5+\beta)}{e^{21\lambda_t}} \quad (14)$$

where $\lambda_t = \dfrac{1}{\lambda + 0.08(2.5+\beta)} - \dfrac{0.035}{1+(2.5+\beta)^3}$

and $\lambda = \dfrac{\omega_r R}{\upsilon_\omega}$

The wind turbine's maximum mechanical output power is defined as a function of mechanical power coefficient ($C_{p\,max}$), optimal wind or rotor speed (ω_{opt}) and turbine blade radius as (15). Solving the equations from (12) to (14), C_p can be expressed as (16).

$$P_{\max} = \frac{1}{2\lambda_{opt}^3}\pi\rho C_{p\max}R^5\omega_{opt}^3 \quad (15)$$

$$C_p = \frac{1}{\left(\dfrac{\upsilon_\omega}{R + \omega_r + 0.08\beta\upsilon_\omega}\right) - \left(\dfrac{0.035}{\beta^2+1}\right)} \quad (16)$$

Now the turbine and the generator modelling is expressed in terms of inertia constants to evaluate the effect of the loading on the system [20]. The turbine, generator and system inertia constants (H_t, H_g and H_{sys}) as,

$$2H_t\frac{d\omega_0}{dt} = T_m - K_{sh}\theta_s - D_{sh}(\omega_t - \omega_r) \quad (17a)$$

$$2H_g\frac{d\omega_0}{dt} = -T_e + K_{sh}\theta_s + D_{sh}(\omega_t - \omega_r) \quad (17b)$$

$$\frac{d\theta_s}{dt} = \omega_0(\omega_t - \omega_r) \quad (17c)$$

$$2H_{sys}\frac{d\Delta f}{dt} + D\Delta f = P_g - P_\omega - P_L \quad (17d)$$

$$H_{sys} = \sum_{i=1}^{n}\frac{H_i\omega_{mi}^2/2}{S_{sys}} \quad (17e)$$

$$P_{de} = (1-d\%)P_{MPPT} \quad (18)$$

Where, ω_0, ω_r, ω_t, and ω_{mi} are the angular base speed, rotor speed, turbine speed before the gearbox and nameplate rotor angular velocity (mechanical) of the ith generator. T_m and T_e are turbine and EMT of the DFIG. Here shaft stiffness (K_{sh}), shaft damping constant (D_{sh}), and the torsion twist constants (θ_s). From equation (17e), we can observe that the wind resources penetration (S_{sys}) raises, the inertia of the system (H_{sys}) decreases considerably. The number of the generators (N), ith turbine-generator combined moment of inertia (H_i), S_{sys} is rated ability of complete power system network. Now, the effect of percentage de-loading (d%) on output generation of the DFIG (P_{de}) with respect to MPPT based real power generation of the DFIG is given by (18).

The de-loading has an effect and will decrease the DFIG power generation and has to be taken seriously for the wind energy conversion system to maintain power system load balancing.

C. Simplified Wind Turbine Model for Frequency Studies

The change in frequency in any one area is dF, the low-pass filter time constant is T_r, washout parameters are T_{w1} and $1/R_1$ is conversion gain to convert to rotor speed. The rotor speed is limited within lower and upper limits. For DFIG (0.6 to 1.3 p.u.) are speed limits for safe and better operation considering gearwheel and other turbine-generator set parameter safety. The output of this speed gives the reference rotor speed value at that instant. The change in wind rotor speed is given by d□, here in our study, it is considered as constant and zero. The speed change error is given to the PI controller and added to the speed error reference parameter. The reference and actual speed are given with wind turbine time constant is (T_{a1}) gives the real power flow. The power flow is cut-off between the minimum and maximum values and this is the change in real power flow change. The sub-system model of the DFIG wind energy conversion system for the load frequency response [22] is shown in Fig.1. The rotor speed lookup table and inertia parameters are also shown.

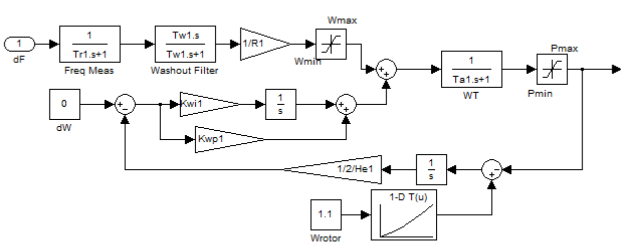

Figure 1. DFIG based sub-system model for load frequency control.

4. Two-Area Testbed System & Compensating Systems Design Considered in the Case Study

This section gives the details of the testbed system that is considered for study as well as the design of SMES and FACTS devices in the following subsections.

A. Two-Area Test Bed System Under Study

The load frequency control study for a two-area generation system is shown in Fig.2a. This system is having two areas connected by a tie-line with an equivalent impedance of transmission line as X_{12}. The current is expected to flow from area 1 to area 2. If due to load switching or generation scheduling, frequency, the real power will change and reach a steady-state after certain oscillations based on these disturbances. To improve the oscillations damping FACTS devices are used. In area 1, the voltage is at an angle $V_1\angle\delta_1$ and in area 2 is $V_2\angle\delta_2$. The angle injected/absorbed by the FACTS device is $1\angle\phi$, therefore voltage at bus 2 is $V_1\angle(\delta_1+\varphi)$. This angle can be positive or negative based on disturbance and oscillation value. Based on the effective control of this angle Φ, that much effective the FACTS device. Each area consists of GENCO, load and WECS as shown in Fig. 2b. The WECS is a DFIG based system that will be dealt with in the next section.

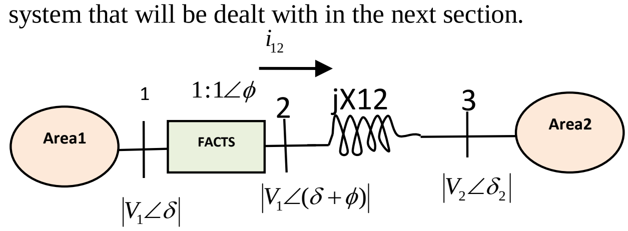

Figure 2a. Two area system under study with FACTS devices

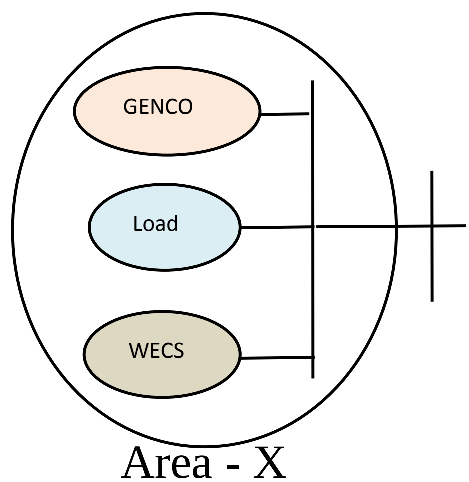

Figure 2b. One area source, load schematic

Due to the disturbance like load switching, there will be frequency oscillations as well as power oscillations. If frequency oscillations are not damped effectively, the system will collapse leading to reliability issues. If frequency regulation is improved, power oscillations are controlled effectively and further reactive power oscillations to a certain extent. The real and reactive power and frequency oscillations can be mitigated using proper FACTS devices with its control strategy. Hence frequency regulation is important for real power and frequency oscillations damping. The two area LFC system with DFIG and SMES compensation is shown in Fig.3.

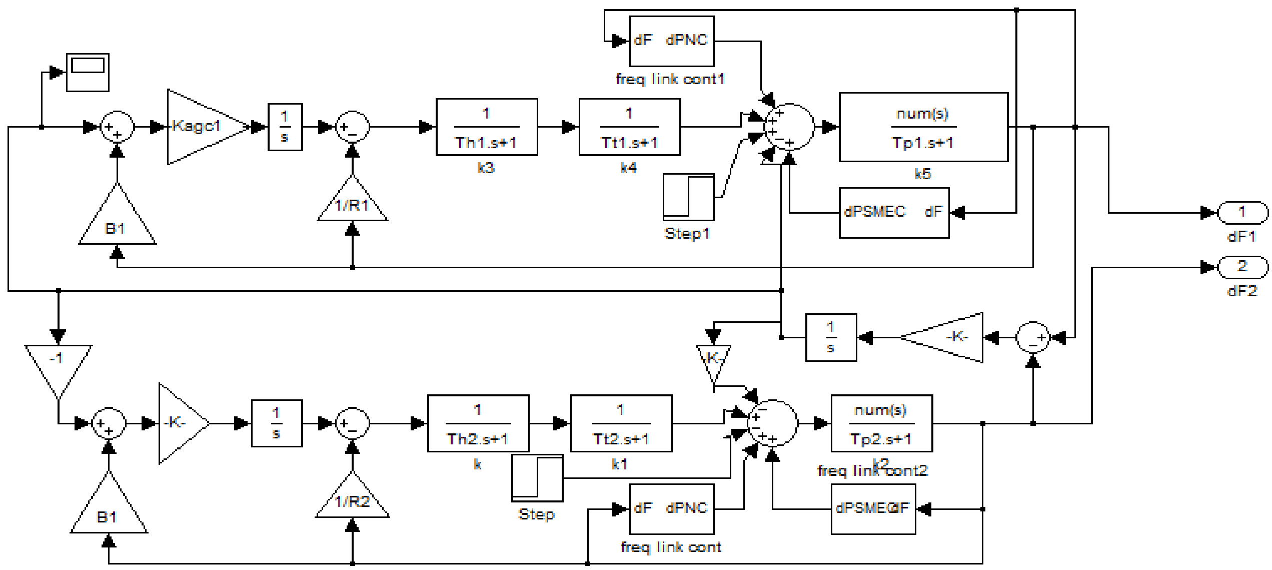

Figure 3. Two-area system with DFIG and SMES storage system designed sing MATLAB software

B. Design of SMES and FACTS Devices

The SMES internal block diagrams are shown in Fig.4a and that of TCPS is shown in Fig. 4b(i) and its connection diagram to a network is shown in Fig.4b(ii) [16]. The SMES model is designed for a two-area generation control is given by equation (19a) [23]. This SMES storage device is costlier than the battery and also requires more maintenance, has more losses, but is an effective device in terms of compensation of mostly reactive power and frequency.

$$\left.\begin{aligned} &\Delta P_{tie12}(s) = \frac{2\Pi T_{12}}{s}\left(\Delta F_1(s) - \Delta F_2(s)\right) + A_1 \\ &where, \\ &A_1 = K_f\left(\frac{1+T_1 s}{1+T_2 s}\right)\left(\frac{1+T_3 s}{1+T_4 s}\right)\left(\frac{K_{SMES}}{1+T_{SMES}\, s}\right)\Delta F_1(s) \end{aligned}\right\} \quad (19)$$

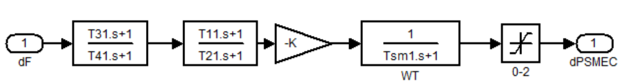

Figure 4(a). Internal block diagram of SMES designed in Simulink

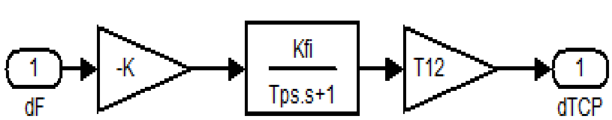

Figure 4b(i). Internal block diagram of TCPS

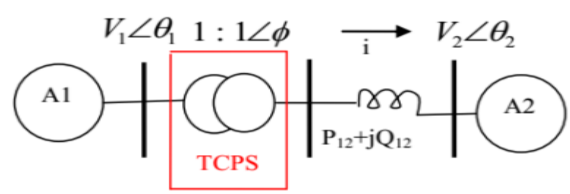

Figure 4b(ii). Network diagram

$$\left.\begin{aligned} &\Delta P_{tie12}(s) = \frac{2\Pi T_{12}}{s}\left(\Delta F_1(s) - \Delta F_2(s)\right) + A_2 \\ &where \\ &A_2 = T_{12}\left(\frac{K_{\varphi}}{1+T_{TCPS}\, s}\right)\Delta F_1(s) \end{aligned}\right\} \quad (20)$$

The internal block diagram as a transfer function model and connection diagram of thyristor controlled capacitor storage phase shifters (TCPS) in a two-area network is shown in Fig.4b(i) and Fig.4b(ii). The area 1 and 2 voltage and its load angle is represented as V_1, V_2 and θ_1 and θ_2, the compensating angle is ϕ_1. The TCPS for a two-area system is represented by the (20).

The TCPS is one of the better FACTS devices which is connected in cascade to a network used for real power flow and frequency regulation in a power network. This device is cheaper than SMES, effective, promising, rapid in action, requires lesser maintenance and longer life. Compared to this SSSC is also a series device, is quicker than TCPS with longer life, better controllability even for a very large system. But it is more complex and costlier than TCPS. Equation (21) describes the power and frequency control operation in a tie-line and the transfer function is in Fig.4c(i) and the network connection of SSSC to a two-area system is shown in Fig.4c(ii).

$$\left.\begin{aligned} &\Delta P_{tie12}(s) = \frac{2\Pi T_{12}}{s}\left(\Delta F_1(s) - \Delta F_2(s)\right) + A_3 \\ &where \\ &A_3 = K_1\left(\frac{1+T_1 s}{1+T_2 s}\right)\left(\frac{1+T_3 s}{1+T_4 s}\right)\left(\frac{K_2}{1+T_{SSSC} s}\right)\Delta F_1(s) \end{aligned}\right\} \quad (21)$$

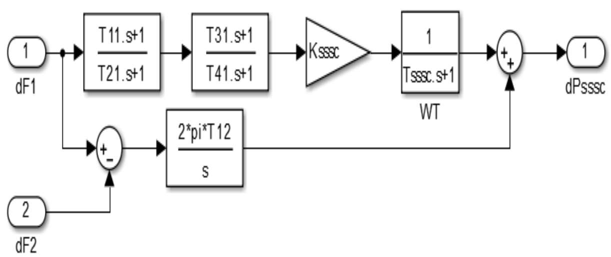

Figure 4c(i). Internal block diagram of SSSC

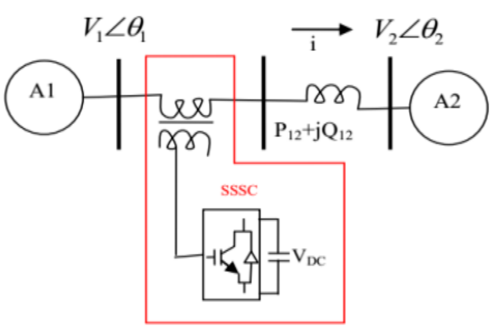

Figure 4c(ii). Network diagram

The internal block diagrams of UPFC and IPFC are shown in Fig.4d(i) and 4d(ii). The UPFC is a single bus hybrid device with SSSC in series to the network and Static Compensator (STATCOM) is a shunt device. Hence, the performance of UPFC is better than SSSC as it is having it and also STATCOM. This makes the UPFC costlier, complex, more requirement of maintenance, more floor space, and lesser reliable, but is more effective in frequency compensation, power loss control, power flow ability, improves stability and loadability limit and has better dynamic operation than any FACTS device that is connected in a single line. The interline power flow control (IPFC) is a two-device single unit series device containing two SSSC devices in two lines or multiple lines. The IPFC is prevalent when compensation is required in more than a single transmission line. This IPFC is a better device than UPFC when voltage, real and reactive power flow, frequency, load angle, losses and stability of a system is considered in two lines, while UPFC will do for a single line. The equations describing the UPFC and IPFC tie-line frequency and power flow regulation can be expressed as in (22) and (23). The parameters and coefficients are shown in Appendix [13 and 16].

$$\Delta P_{UPFC}(s) = \left(\frac{1}{1+T_{UPFC} s}\right)\Delta F_1(s) \quad (22)$$

$$\Delta P_{IPFC}(s) = \left(\frac{1}{1+T_{IPFC} s}\right)\left(K_1\Delta F_1(s) + K_2\Delta P_{12}(s)\right) \quad (23)$$

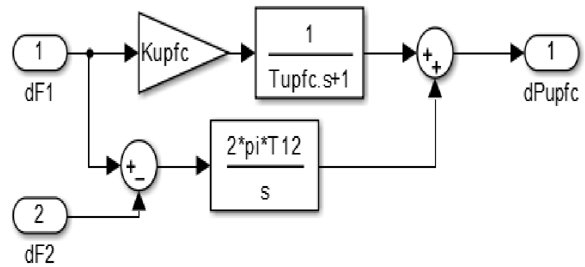

Figure 4d(i). Internal diagram of UPFC

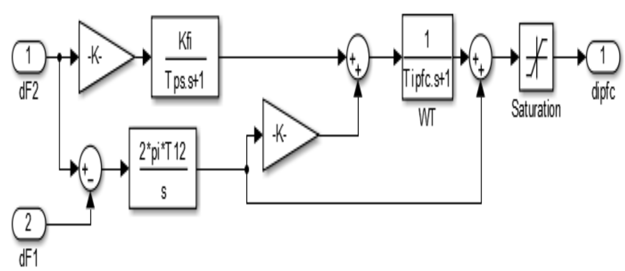

Figure 4d(ii). Internal diagram of IPFC

5. Results and Analysis

The influence of various FACTS devices and SMES connected to a circuit shown in Fig.2a is discussed in this section under two cases. Case-1 studies the operation of load change in area-1 at 1 second with SMES, TCPS and hybrid combination of both for a 0.1 p.u. increase and the effect of frequency change and effectiveness among these two are analyzed. Later in case-2, the performance of TCPS, SSSC, UPFC and IPFC are studied and their effectiveness is analyzed.

In case-1, the objective is to choose a better device among SMES and TCPS, so almost the same rating devices are considered for the same two area bus network. From Fig.5(i), it is observed that variation in the frequency in area-1 (top) without any energy storage device (NO ES) is having more deviation of -0.0275 p.u. while SMES is having a very small deviation with lesser oscillations and settled quickly. When TCPS and a hybrid combination of TCPS and SMES is observed, the deviation in frequency is very lesser than with SMES, which is almost negligible even for a 10% change in load suddenly. When comparing TCPS and hybrid devices in this case, the hybrid device is very dynamic and quicker in response. Compared to area-1, area-2 is having lesser frequency deviation and frequency response is quicker as load change is in area-1 only and its influence to a certain extent is observed in area-2 as it is connected to a tie-line. Hence, the hybrid system is best, next is TCPS and then SMES is better in operation.

For case-2, TCPS, SSSC, UPFC and IPFC based FACTS devices are considered for the same bed system, but with 50% increase in the load. It can be seen in Fig.5(ii) such a large load change in one area will persuade remaining areas connected to a tie-line. There is almost 0.6 p.u. change in the frequency, which is very dangerous to a system and it will trip the network with the help of frequency protection relays. The sustained oscillations are observed in area-1 (top) and area-2 (bottom) is with TCPS. The frequency deviation is controlled by changing its phase angle, as it is a little lesser predominating, oscillations are observed. The oscillations with ±0.2 p.u. are with lesser frequency (or higher time period) with TCPS as is a device having resonating column elements like inductor and capacitor. As describes in equation (18), TCPS is like a lag compensator of 1st order system and its frequency of oscillations depends on its time constant and its amplitude depends on the gain constant.

Now, SSSC is compared for the analysis, it is a better device than TCPS and is a 3rd order system with higher performance characteristics and better dynamic response as in equation (19). Hence, a small deviation of 0.02 p.u. or 2% is observed at the instant of load change and completely became zero in 12s. The UPFC which is a combination of SSSC and UPFC is described with a single order transfer function, but with a different arrangement of its closed-loop and is having a better time constant and gain values than SSSC. Hence, this UPFC with better closed-loop and hybrid characteristics is performing better than SSSC with a deviation of 0.012 p.u. and settled in 8 seconds. Now, finally, IPFC which is a dual-SSSC in both areas is found to have 0.006 p.u. frequency deviation and settled in less than 5 seconds. Therefore, among all the devices, the IPFC is the best with the least deviation to the frequency with 50% rapid change in load and quicker in response. The work can also be observed for larger grid-connected bus systems or with multiple generator source types, or observing wind turbine-generator side disturbances like wind speed variation, rotor shaft speed variations etc. The work may be further extended with the use of advanced controllers like ANFIS, Fuzzy-PID and other promising metaheuristic algorithms like teacher-student learning, ant-bee, ant-lion etc.

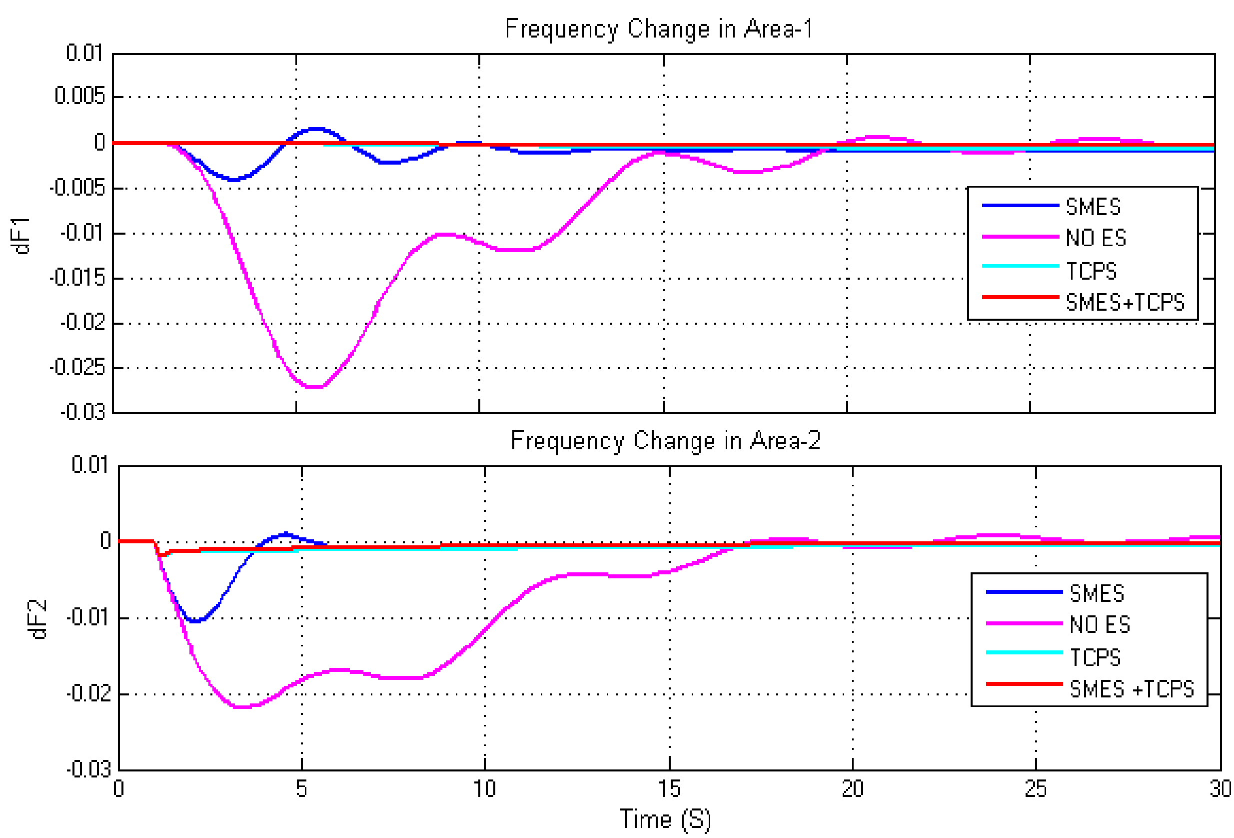

Figure 5(i). Area 1 and 2 frequency change observed in case-1

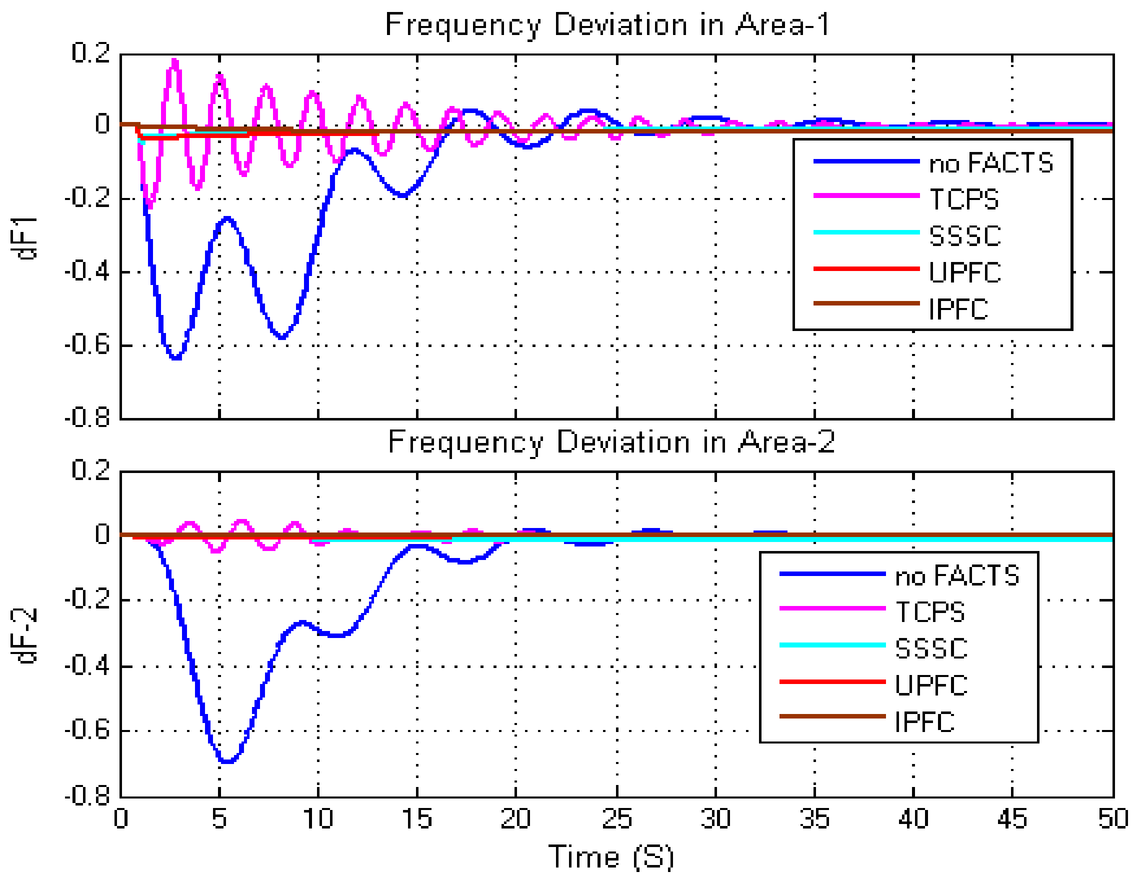

Figure 5(ii). Area 1 and 2 frequency change observed in case-2

6. Conclusion

In this paper, SMES, TCPS, SSSC, UPFC and IPFC are analyzed for a two-area network with sudden load change in area-1 and the compensation characteristics of the devices are observed in both areas. If in one area, a rapid variation in the load is observed, this load change in the other area is influenced as both the areas are connected to a tie-line network. A small deviation in load in one area may not change the frequency considerably in other areas, but a large change in the load will influence to a greater extent, that may trip both areas from the grid due to large frequency and power flow deviations. Hence, protection of the system and reliability are considered, these external energy or FACTS devices play a vital role in controlling a surge change in frequency or power flow deviation. Among all these devices considered, SMES is good, the better than this in performance increasing order is TCPS, SSSC, UPFC and the best device is IPFC. This IPFC is having more advantages than UPFC such as lesser complex, lesser switching elements and can be connected to more lines at a cheaper price than UPFC. The work can be extended further using advanced controllers like ANFIS, Fuzzy-PID and other promising meta-heuristic algorithms like teacher-student learning, ant-bee, ant-lion etc.

Appendix. Simulation Specifications

Parameters	Values
Synchronous generator, DFIG and tie-line parameters:	K_{agc1}=0.05; R_2=3; K_{agc2}=0.05; H_{e1}=3.5; H_{e2}=3.5; T_{12}=0.0866; K_{wp1}=1.58; K_{wi1}= 0.1; K_{wi2}=0.1; T_{t1}=1; T_{t2}=1; T_{w1}=6; T_{w2}=6; K_{wp2}=1.61; T_{a1}=0.2; T_{a2}=0.2; K_{p1}=12; K_{p2}=12; R_1=3; T_{h1}=0.1; T_{h2} and Th2=0.1; T_{p1}=10; T_{p2}=15; T_{r1}=0.1; T_{r2}=0.1
SSSC parameters:	K_{sssc}=15.91830; T_{sssc}=0.0815254; T_{11}=0.0814835; T_{21}=0.0815148; T_{31}=0.082393; T_{41}=0.081295
UPFC parameters:	T_{upfc}=0.017801; K_{upfc}=1.0
IPFC parameters:	K_{ipfc1}=3.1270; K_{ipfc2}=3.12116; T_{ipfc}=0.006145
SMES parameters:	T_0=0.07; T_{sm}=10.50; T_{sm1}=0.2151; W_{max}=1.4; P_{min}=0; W_{min}=0.0; K=10.1378; T_{11}=0.587; T_{21}=0.157; T_{31}=0.0576; T_{41}=0.2317; K_{fi}=24.9004; P_{max}=3; K_1=20.2188; T_{ps}=0.0016172; B_1=1.1

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