Voltage Control by Optimized Participation of Reactive Power Compensation Using Fixed Capacitor and STATCOM

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Abstract FACTS devices play a significant role in providing voltage control through adequate reactive power compensation under the conditions of load and input changes. In isolated wind diesel based hybrid electrical system, choosing adequate participation of reactive power compensation device becomes more important because of the following aspects; (i) unlike to grid connected system, additional sources are required for supplying reactive power, (ii) normally self excited induction generators are used for power generation through wind and these generators require reactive power for building up the voltage, (iii) wind generators power output is much affected by changes in input wind speed and these changes require additional reactive power to control the voltage, (iv) similar to input change, load changes also require additional reactive power to maintain the voltage level, (v) compensating device should respond fast for nullifying the voltage deviation in minimum time, (vi) the procedure adopted for reactive power compensation should be economically acceptable even for the last end user in the society. Therefore, the reactive power compensating devices for voltage control in isolated hybrid electric system should be participated optimally by considering these technical and economical aspects simultaneously. In this chapter, MATLAB (programming along with simulink model) based approach is demonstrated for voltage control through optimized participation of reactive power compensation using fixed capacitor as static and STATCOM as dynamic compensator.

Keywords Static Compensator · Dynamic Compensator · Reactive power compensators · Compensation cost · Ancillary services

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1 Role of Reactive Power Compensation

Techno-economical studies in distributed power system have been presented by many researchers. These studies depict that the electrification through traditional centralized generating units is a real challenge for far located remote/rural areas because of geographical diversity, concentrated availability of natural resources and dispersed power demand. Electrification without long transmission lines can be a better option to such far located remote/rural consumers. Because of the remoteness of such non-electrified population, renewable energy can offer a cost effective and environmental friendly means of providing power. In recent years, production of clean energy (renewable ones) by private investors is encouraged. Government in almost all countries are also promoting public participation through several schemes for installing small units of power generation using hybrid systems [1]. Government of India is also promoting to private investors for installing distributed generating units because of technical and economical limitations of supplying grid connected power system at such far located rural areas [2]. Private investors' participation in installing renewable energy system (RES) can be better understood through Fig. 1. It has also been noticed that 88% renewable energy sources are installed by private investors in India [3].

Wind energy is the most promising form of renewable energy for generation of electric power but suffering from intermittent nature of the wind. To provide continuous and reliable power in such far located areas, renewable energy based generators along with conventional fuel based generators can be used without grid connection. Researchers have presented hybrid power generation models in which self excited induction generator (SEIG) and synchronous generator (SG) are used together for generating power through wind and diesel respectively [4–8]. In this

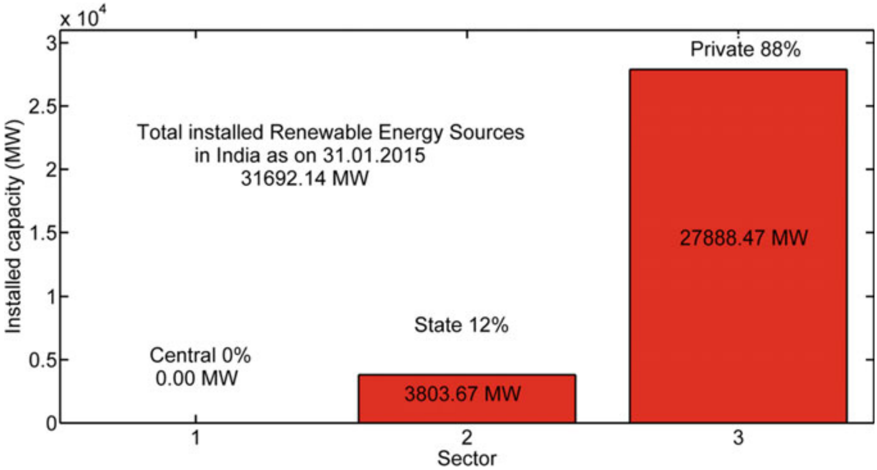

Fig. 1 Participation of different sectors for installing renewable energy system in India

chapter studies are focuses for such wind diesel based hybrid electrical system. Since these electrical systems are isolated from grid so, called isolated hybrid energy system (IHES).

This wind-diesel based IHES is one of the most promising systems to provide continuous, efficient, economical and reliable electrical energy and has a wide scope especially in developing countries. Due to grid isolation, hybrid configuration of generation units, random behaviour of consumers load and evolvement of public-private investors' participation, IHES has many technical and economical issues in their operations. Selection of adequate reactive power compensation for such IHES is one of them which is being focussed technically as well as economically in this chapter.

Problems in electrical systems can be broadly identified in two categories; (i) active power frequency ($P - f$) control, and (ii) reactive power voltage ($Q - V$) control. The $P - f$ and $Q - V$ controls are almost non-interactive in electrical systems because small changes in active power are mainly dependent on changes in generator speed and are almost independent of changes in terminal bus voltage, while small changes in terminal bus voltage are mainly dependent on machine excitation and are almost independent of changes in generator speed. Since, excitation control is a fast acting with less time constant encountered as that of generator field, while power frequency control is a slow acting with more time constant as contributed by turbine and generator moment of inertia. So, the time constant for $P - f$ control loop is much larger than that of the $Q - V$ control loop. Even in conventional grid connected power system, active power is exported on transmission line to load centre but reactive power required by load is produced closer to the requirement to avoid large transmission losses and voltage variations. It should also be noticed that the production of reactive power involves only capital cost but no fuel cost. Therefore, $P - f$ and $Q - V$ control loops are assumed to be decoupled in power system and the problem of reactive power voltage ($Q - V$) control can be focussed separately at load centres.

The IHES is designed with the help of diesel, a non renewable energy source to provide continuous and reliable supply and wind, a renewable energy source to provide environmental friendly energy supply. The self excited induction generator is used to extract power from wind while the synchronous generator is used to extract power from diesel in this isolated hybrid energy system. The major disadvantage of self excited induction generator is the requirement of reactive power for its operation. In grid-connected system, induction generator can be excited from either grid or capacitor banks, whereas in an isolated system, reactive power excitation along with load reactive power demand can only be achieved through reactive power compensators. Apart from steady state reactive power requirement, dynamic conditions also require reactive power for regulating the voltage response due to instant changes in load demand and input power in system. The automatic voltage regulator (AVR) of the synchronous generator, connected in parallel with induction generator in this IHES, may not be able to offset the reactive power mismatch as its prime function is to generate the real power for load keeping terminal voltage within limits with minimum over and under excitation.

Therefore, reactive power compensators are required for additional reactive power demand in system. Deficiency in this extra reactive power demand can cause severe problems of large voltage fluctuations at load terminal and therefore, affect the quality of supply. In absence of the proper voltage control, this may even damage the system stability. Voltage control problems are complex in nature especially for heavily loaded power system and unbalance in generation. Voltage control is one of the six ancillary services that is used to maintain the voltage profile through injecting or absorbing reactive power [9]. Therefore, proper reactive power compensation techniques are required to ease the voltage control problems in IHES. Hence, as a technical issue, if the system operator does not consider impact of reactive power on voltage control, it may move the system toward voltage instability point. Therefore, sufficient fast acting reactive power reserve is necessary to prevent unacceptable voltage deviation after any system disturbance or due to load uncertainty [10]. This is called $Q - V$ control loop problem and is mainly focussed for reactive power compensation and voltage control studies of this chapter for IHES.

Since, the optimal and adequate reactive power deployment in the competitive electricity markets is identified as one of the important ancillary services and is provided by the Independent System Operator (ISO). The procurement of reactive power as an ancillary service involves cost investment and thus needs to be remunerated. Effective regulatory policies are necessary to ensure an adequate supply of reactive power at reasonable cost whether in independent or integrated power system. The rules for procuring reactive power can affect whether adequate reactive power supply is available, as well as whether the supply is procured efficiently from the most reliable and lowest cost sources. Fast acting device for reactive power compensation gives better results of voltage regulation in system but at the same time they increase system compensation cost much. On the other side, static compensator has very low cost but alone cannot be suitable for reactive power compensation in system. Hence, economic analysis of reactive power compensation in IHPS is also an important aspect.

Therefore, a hybrid use of compensating devices; static as well as dynamic compensators, can be used for techno-economic solution of reactive power compensation in IHES for controlling the system voltage under specified limits. In this chapter, the technical benefits from the hybrid participations of static and dynamic reactive power compensators in voltage control studies are mainly focussed. A MATLAB program is developed for choosing the best possible participations of fixed capacitor and STATCOM for voltage control studies in system during steady state and dynamic conditions.

2 Introduction to Reactive Power Compensators

In isolated hybrid electrical system, reactive power compensation plays a key role in controlling the system voltage. The reactive power support, essential to maintain the voltage profile and stability of the system, is one of the six ancillary services specified in the FERC order no. 888 [11]. Reference [12] explains two types requirement of reactive power for system operation; (i) under steady state and (ii) under dynamic conditions. Reference [13, 14] assumes that the generators are obligated to provide a certain amount of reactive power (up to generator's mandatory limit) without any payment. Synchronous generator is primarily used to generate real power to system therefore only mandatory limit reactive power is supposed to be released form it without considering opportunity cost through it. In Reference [15] voltage response is explored with external rotor resistance along with excitation capacitor for autonomous SEIG. Wang et al. [16] proposed an analysis to predict both minimum and maximum values of capacitance required for self-excitation of a three phase induction generator.

In hybrid electrical system reactive power compensation becomes complex due to the parallel operation of different generators along with load influence. Stand-alone operation of a squirrel-cage induction generator based WECS with regulated output voltage and frequency requires either an asynchronous link (ac–dc–ac) power electronic converter or a matrix converter. The excitation capacitor bank of large rating has to be implemented with thyristors rectifier because thyristors rectifier can only absorb active and reactive powers. This makes the system efficiency low. Therefore, shunt connected VSI with a capacitor and a switched resistor in the dc bus is proposed alternatively in [17]. References [18, 19] proposed a hybrid exciter in which one set of a parallel connected three-phase fixed frequency pulse width modulation (PWM) inverter fed from a battery and fixed capacitor bank is used. In order to avoid the problem of mismatch of reactive power generation and absorption in system switch capacitor may be used in place of fixed capacitor. But switched capacitor can only give discrete solutions for avoiding reactive power mismatch in system. A variable reactive power source is required match the generation and absorption of reactive power. Three SVC models are explained for reactive power compensation in a hybrid system [20].

The STATCOM device is the static counterpart of the rotating synchronous condenser but it generates/absorbs reactive power at a faster rate. The STATCOM employs a voltage source inverter (VSC), which internally induces inductive or capacitive reactive power as required. In principle, it performs the same voltage regulation function as the classical SVC but in a more robust manner and is also advantageous than that of SVC [6]. It goes on well advanced energy storage facilities, which open the door for a number of new applications, such as energy markets and network security [21]. Reference [22] proposes STATCOM transient stability and power flow models as improved versions of models previously proposed in the literature. Reference [23] proposes a new method, called the flatness-based adaptive control (FBAC), for STATCOM voltage regulation.

2.1 Introduction to Reactive Power Market

Private investors in deregulated and isolated mode of electricity markets in many countries worldwide bring new perspectives for small businesses specializing in energy generation. Wind power generation has better options for investment and therefore, attracts the private sector [24]. Size optimization is among the most important studies in order to achieve efficient and economical utilization in the hybrid system [25]. Reference [26] discusses the problem in dealing two objectives simultaneously (costs and unmet load) which are usually in conflict, since a reduction in design costs implies a rise in unmet load and vice versa. Reference [27] suggests that voltage and reactive power support are linked to each other and reactive support is distinguished as an ancillary service, which can facilitate active power transportation in system. Modal analysis technique is proposed for the management of reactive power generation to improve the voltage stability margin in [28]. Reference [29] addresses the problem of how to pay the voltage support providers; and how to allocate the incurred costs to the users. Reference [30] focuses on two aspects; voltage profile management and reactive dispatch and voltage regulation in isolated system.

In the new open access environment, in pursuit of profit, the power producer has incentive to sell active power as much as possible. A generator can sell its active power if only there is enough reactive power to support it. Otherwise, the generator is no longer able to sell active power due to system security constraints. So, it is essential to establish a mechanism for financial compensation of the reactive power ancillary service [31]. Different methods are used in different electricity markets for reactive power procurement. As main philosophy of the electricity markets, the system operator tries to provide reactive power with the lowest possible cost. Also, because of important role of reactive power in network operation and security, many researchers have considered technical issues as well as economic issues. Reference [32] provides a techno-economic analysis to decide configuration of autonomous system on the basis of power quality, system overall cost, payback time and emission of green house gases. The effects of load variation on system configuration and cost are also examined.

Although reactive power costs constitute only about 1% of total power industry costs [33], it's still important to make it clearly analyzed when the reactive power market is concerned. According to economics aspects, total cost of any commodities can be divided in two components; fixed cost component and a variable cost component. The capital investment of equipments are categorised into fixed cost category while costs connected to the output quantity are categorised into variable cost category. Without any fuel cost to generate reactive power, the variable cost of generators include maintenance and operation cost and opportunity cost. Equipments like synchronous condensers, shunt capacitors, STATCOMs, and SVCs don't produce real power, so they don't have opportunity cost.

Reactive power cost curve of a synchronous condenser can be formulated including operating cost and investment cost. Reference [34] deals with evaluation of capacitive reactive power cost under the deregulation environment. For the cost assessment of reactive power, the duration curve of reactive power demand is introduced to take into account the investment costs. Capacitor reactive power cost function is given in [35]. Cost functions of UPFC, TCSC and SVC are given in polynomial form in [36]. Furthermore, cost functions are incorporated for bids of suppliers and consumers and investment costs of FACTS devices. Cost function is defined as the sum of capital cost and installation cost.

Model presented in many papers optimize the certain objective function (e.g., reactive power production cost minimization or social welfare maximization) using optimal power flow (OPF) models and use of fixed capacitor and FACTS device is proposed for future work. The resources for reactive power such as synchronous generators, synchronous condensers, capacitor banks, reactors, Flexible AC Transmission System (FACTS) devices are owned by the independent generators or local suppliers. Reference [37] defines costs for the service performed by these devices, then it proposes an optimal co-ordination method which allows distributors to select, for every operating condition, the more profitable combination of reactive sources in order to maintain the network voltage levels within a desired range and to minimise the regulation action global cost.

2.2 Selection of Dynamic and Static Compensator

In most of the present researches available on wind diesel based IHES, the main thrust is on technical benefits using fast acting compensating devices for reactive power compensation and voltage control while economic issues of reactive power compensation are not focussed by researchers yet. The system dynamic responses can be suppressed in least time within the permissible range by use of FACTS devices namely; Static VAR Compensator (SVC) or Static Compensator (STATCOM). FACTS device produces better responses in terms of system voltage control compare to the conventional compensation devices viz. fixed capacitor (FC), switched capacitor and synchronous compensator. Although SVC/STATCOM give better results as discussed in various research papers [4, 20], their cost is very high compared to fixed capacitor. It is well known that a fair pricing of such a service can lead to market liquidity which in turn results in approaching the optimal condition. Therefore, for a competitive market environment, the economic viability should also be considered with engineering requirements. Getting the benefits through Government promotional schemes, private investors can develop isolated units for continuous power supply to far located remote area. At such rural/remote areas, the end users are not too developed economically to pay more tariff rates for generating companies (Gencos). Even most of the time Government has to subsidize the power to such consumers and therefore, power supply continuity is a prime concern however its quality degradation may be allowed up to some extent to keep the cost low. And therefore, method to reduce the compensation cost for the consumer is proposed in this chapter.

Reactive power demand in system can be classified by two categories; (i) fixed demand, and (ii) variable demand. Fixed demand includes steady state load demand and induction generator excitation. Variable demand includes load and induction generator reactive power demand due to sudden changes in system conditions. The characteristic comparison of voltage control equipment, i.e., fixed capacitor (FC), SVC, and STATCOM (ST), is mentioned in Table 1 [38]. For voltage control, reactive power is required through compensators in IHES. This compensation may be

Table 1 Characteristics comparison of voltage support equipment

Equipment	Equipment type	Response speed	Voltage support	Operating cost
FC	Static compensator	Slow	Poor, drops with V^2	Very low
SVC	Dynamic compensator	Fast	Poor, drops with V^2	Moderate
STATCOM	Dynamic compensator	Fast	Fair, drops with V	High

achieved using static, dynamic or combination of both types of compensators. As in Table 1, dynamic reactive power compensators (SVC and STATCOM) give best results for voltage control [2, 4, 6], but their cost is very high compared to that of static reactive power compensator (FC). On the other side, the cost of static compensator is very low, but they alone are not capable of providing the adequate solution of voltage regulation.

Before deciding the compensation techniques, following observations must be noticed;

1. Reactive power is required for steady state and dynamic conditions. Steady state requirement can be supplied by static and/or dynamic compensating device but dynamic conditions can only be supplied by dynamic compensating device [12].
2. Static compensators are cheaper but cannot regulate to system voltage for fast acting changes in system [4].
3. Dynamic compensators have good characteristic for regulating the system voltage during sudden changes but their use make system's compensation cost very high [38].
4. Participation of static compensator with dynamic compensator can be allowed up to the extent where system voltage response remain within its pre defined acceptable range [30].

Hence, a combination of static as well as dynamic compensating devices can be used to mitigate system fixed demand while fast respond dynamic compensators are necessarily required in suppressing the dynamic demand of the system in minimal time. The methodology may be adopted for deciding the participation of static and dynamic compensators including these two behaviours of demand. The concept for reducing STATCOM size with a fixed capacitor for self-excited induction generator is compared in Ref. [39] for full rating of STATCOM alone and half rating shared with fixed capacitor along with STATCOM. Since the IHESs have both fixed demand and variable demand so static compensator alone cannot be installed to mitigate the effect of sudden changes in load and wind input power. These changes may result in a serious problem of large voltage fluctuation without proper reactive power compensation. Dynamic compensator alone can mitigate the voltage control issues but the compensation cost becomes high through it. To overcome this problem, STATCOM and fixed capacitors, both are installed in the system together to control reactive power and to minimize voltage fluctuations. The proper selection of both static as well as dynamic compensators simultaneously may provide the optimum solution between the system voltage control and cost of compensation.

Therefore, the selection of STATCOM and fixed capacitors ratings depend on the two aspects; overall cost of compensation and system voltage response [40]. In this chapter, a cost analysis is done for reactive power participation in isolated hybrid electrical system through fixed capacitor as static and STATCOM as dynamic compensator.

3 Reactive Power Compensation Cost Analysis

This chapter presents the technical benefits from the hybrid participations of static and dynamic reactive power compensators in voltage control studies. A method of reactive power compensation pricing is proposed by including static and dynamic compensators in system. Concepts about reactive power compensation as ancillary service in power system, method of cost formulation and cost formulae for different compensating devices are discussed in this section.

3.1 Reactive Power as an Ancillary Service

Any end user of power system is implicitly a consumer of ancillary services who is demanding continuous and quality of power supply. For power producers, ancillary services are mainly defined by the basic contributions they make to fulfil the system functions. Besides the supply of active power, they supply or absorb reactive power and control the voltage as well as contribute to maintaining the system frequency. According to North American Electric Reliability Council (NERC), ancillary services can be categorized into three categories;

Category-1: Services required for routine operation
Category-2: Services needed to avoid blackout
Category-3: Services needed to restore after blackout.

In category 1, voltage control has prime importance in the system along with other ancillary services like system control, regulation, load following, energy imbalance. In isolated hybrid power system, voltage is controlled by the compensation of reactive power with the help of synchronous generators, static and dynamic compensator. These reactive power devices have several characteristics for consideration such as their dynamics, response speed, voltage changing ability, capital costs, operating costs, and opportunity costs.

It has been suggested that the independent generators or customers install their own reactive support resources and the ISO should enter into contracts with those independent generators or customers for such provision. These reactive support resources may be synchronous generators, synchronous condensers, capacitor banks, reactors, static VAR compensators and FACTS devices. Perceived demand conditions, mix of the load and availability of reactive power resources should be considered for procurement of reactive power services [1].

Reference [41] describes that reactive power through generator and synchronous condenser is recognized as "ancillary services." Changes at the policy level are necessary to include other reactive power sources such as capacitors, reactors, SVCs and FACTS devices etc., as ancillary services. This would enlarge the market and increase the competition, and inevitably increase the market efficiency and fairness.

In this chapter, it is being assumed that IHESs are owned by private investors who are committed to provide electricity on cheaper rates for far located remote area based end users. It is also assumed that power quality degradation within permissible range can be acceptable for reducing the cost in such remote areas. Available and possible pricing options for reactive power compensation are discussed in this section first. Since reactive power can be supplied by synchronous generator, FC and STATCOM in system, the cost issues by them are also being discussed here.

3.2 Pricing Options in Reactive Power Compensation

Reactive power pricing was started with the Commission's Order No. 888, its Open Access Rule, issued in April 1996. In that order, the Commission concluded that "reactive supply and voltage control from generation sources" is one of six ancillary services that transmission providers must include in an open access transmission tariff. The main aim for reactive power procurement is to ensure the adequate supplies of reactive power (including reactive reserves) in the system at least cost for steady state and dynamic conditions. Optimization of reactive power cost is required because; the static compensators having lowest cost cannot always be reliable and adequate producers of reactive power as dynamic compensators. Dynamic compensation might be expensive reactive power procurement but they must sometimes be purchased even if cheap reactive power sources are available. Two general ways have been suggested for providing reactive power though generators compensation in literature.

3.2.1 Capacity Payment Option

In capacity payment option generator is paid in advance for the capability of producing or consuming reactive power. The payment could be made through a bilateral contract or through a generally applicable tariff provision. Once the generator is paid, it could be obligated to produce or consume reactive power up to the limits of its commitment without further compensation when instructed by the system operator. To ensure that the generator follows instructions in real time, the generator could face penalties for failing to produce or consume when instructed. Currently, this is the most common method for compensating reactive power providers. Four methods are suggested for capacity payment option as;

- A cost-based payment

- Capacity market payment
- Prices determined through auction
- Pay nothing.

3.2.2 Real-Time Price Option

In real-time price option, generator is paid in real-time for the reactive power that it actually produces or consumes. Under this option, the generator is paid only for what it produces or consumes, but it pays no penalty for failing to produce when instructed. Four methods are also suggested for real time capacity payment option as;

- Pay nothing
- Unit-specific opportunity costs
- Market clearing prices determined through auction
- Prices (or a pricing formula) announced in advance.

Reactive power spot pricing can be adopted by including the features of both capacity payment option and real time capacity payment option. A method of reactive power compensation cost analysis is proposed by including static and dynamic compensators in system keeping compensation through synchronous generator constant and equal to its mandatory limit. This proposed method includes two important aspects for reactive power compensation; first, to encourage efficient and reliable investment for steady state reactive power demand and second, to encourage production and consumption of reactive power from exciting infrastructure for dynamic state demand.

3.3 Synchronous Generator as Reactive Power Service Provider

Synchronous generators are basically used for active power generation; however, they are also able to provide reactive power for security purposes. The synchronous generator's capacity is limited by the armature current, field current and under-excitation limits. The stable operating point of a generator is always restricted to its capability curve boundaries, which are defined according to armature and field winding heating limits. Synchronous generator may generate the reactive power in three regions namely; mandatory cost, cost of loss and opportunity cost, as shown in Fig. 2.

When synchronous generator releases reactive power in mandatory cost region, it does not receive any payment for reactive power production. In cost of loss region, generator is entitled to receive two components of payments availability component and cost of loss component. In opportunity cost region, generator is entitled

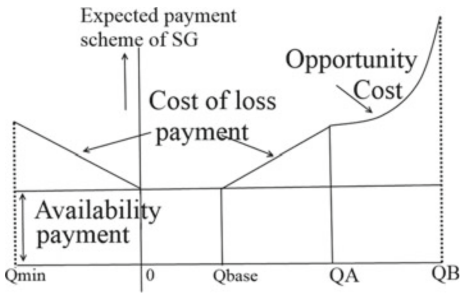

Fig. 2 Reactive power scheme in synchronous generator

to receive payment with its opportunity cost of reduced real power production [38]. Mathematically,

Expectation of Payment Function (EPF) of synchronous generator for reactive power,

$$EPF = Mandatory\,cost + cost\,of\,loss + opportunity\,cost \tag{1}$$

A generator's cost of producing reactive power can sometimes include opportunity costs associated with forgone real power production. Opportunity costs arise because there can be a trade-off between the amount of reactive power and real power that a generator can produce. When a generator is operating at certain limits, a generator can increase its production or consumption of reactive power only by reducing its production of real power as the winding of the synchronous generator is designed for a particular rating of current. Further, this method is somewhat complex, and is only cost effective when a large amount of compensation is needed [9, 20]. For calculating the different points shown in Fig. 2 for reactive power scheme of synchronous generator, i.e. mandatory reactive power (Q_{base}), cost of loss reactive power (Q_A), reserve reactive power ($Q_A - Q_{base}$), and opportunity cost reactive power ($beyond\ Q_A$), following mathematical expressions can be used [42].

For synchronous generator, mandatory reactive power can be calculated by the Eq. (2) in which P_{SG} is the rated real power of generator at $\cos\theta_{SG}$ lagging power factor.

$$Q_{mandatory} = P_{SG,pu} \tan\theta_{SG} \tag{2}$$

From field current limit equations of synchronous generator,

$$\mathrm{P_{SG}} = \frac{\mathrm{3VE_q}}{\mathrm{X_s}}\mathrm{Sin\delta} \tag{3}$$

$$Q_{SG} = \frac{3VE_q}{X_s}\mathrm{Cos}\delta - \frac{3V^2}{X_s} \tag{4}$$

Squaring and adding the Eqs. (3) and (5),

$$P_{SG,pu}^2 + \left(Q_{SG,pu} + \frac{3V^2}{X_s}\right)^2 = \left(\frac{3VE_q}{X_s}\right)^2 \tag{5}$$

For estimating the cost of loss reactive power by synchronous generator, Eq. (5) can be solved for getting the value of $Q_{SG,pu}$. So,

$$Q_{cost\,of\,loss} = Q_{SG,pu} \tag{6}$$

$$Q_{reserve} = Q_{cost\,of\,loss} - Q_{mandatory} \tag{7}$$

The lost opportunity cost can be determined above the rated reactive power requirements and below the maximum limit reactive power generation from the generators.

Since, the synchronous generator should not be entitled to receive any payment for reactive power production in mandatory cost region. It is assumed that synchronous generator provides reactive power equal to mandatory limit only in the study.

3.4 Fixed Capacitor as Reactive Power Service Provider

The function of cost for capacitor is assumed to be proportional to the amount of the reactive power output purchased and equal to the product of depreciation rate and amount of the reactive power output purchased [11]. Fixed capacitor function of cost (C_{FC}) can be expressed as,

$$C_{FC} = rQ_{FC}\,in\,\$/\mathrm{H} \tag{8}$$

where, symbol *r,* defines the cost or depreciation rate of fixed capacitor Q_{FC}, is the amount of reactive power supplied by fixed capacitor to the system. The rating of the Q_{FC} is in MVAr. The depreciation rate is calculated by the ratio of investment cost and the operation hours of FC. The fixed cost for life span of 15 years is considered as per general practice [35],

$$C_{FC} = 0.132 * Q_{FC}\,in\,\$/\mathrm{H} \tag{9}$$

Example 1 A delta connected capacitor bank having per phase capacitance of 200 μF is connected with a electrical system. The generated voltage with this electrical system is 400 V at 50 Hz. Find the MVAr generated by this capacitor bank. Also find the compensation cost through FC if life span of this capacitor bank is assumed to be 15 years.

Solution For delta connected capacitor bank,

$$V_P = V_L = 400\,\text{V}$$

Reactance for the capacitor is,

$$X_C = \frac{1}{2\pi f C}$$

Reactive power developed by the capacitor bank,

$$Q_{FC} = \frac{3V_P^2}{X_C} \times 10^{-6}\,\text{MVAR}$$

The compensation cost through FC for life span of 15 years is,

$$C_{FC} = 0.132 * Q_{FC}\,\$/\text{H}$$

Using the mathematical expressions given above, MATLAB codes are written for getting the solutions of this example as below.

```
%%% MATLAB codes for compensation cost through Fixed
Capacitor (FC)
>>clear all;
>>clc;
>>vl=400;
>>f=50;
>>c=200e-6;
>>vp=vl;
>>xc=1/(2*pi*f*c);
>>qfc=(3*vp^2/xc)*10^-6            % MVAr generated
>>cost_qfc=0.132*qfc         %    compensation    cost
through FC
```

The results for the program given above are;
For MVAr generated = 0.0302 MVAR
Compensation cost through FC = 0.0040 $ per H.

3.5 STATCOM as Reactive Power Service Provider

An empirical method is available to obtain function of cost for STATCOM. The curve is plotted between the investment costs and the ratings for the different installation of STATCOM. An expression is developed for this as a function of STATCOM rating based on the quadratic polynomial curve fitting method. ST average operating life is also taken same as that of FC i.e. 15 years. The rating of the Q_{ST} is in MVAr in Eq. (10). The expression for STATCOM function of cost (C_{ST}) is given as [43];

$$C_{ST} = \frac{1000 * Q_{ST}}{8760 * 15}\left(0.0002466 Q_{ST}^2 - 0.2243 Q_{ST} + 150.527\right) in\ \$/\mathrm{H} \tag{10}$$

Example 2 In previous Example 1, if same MVAR are being supplied by STATCOM. Find the compensation cost through STATCOM.

Solution The expression for compensation cost through STATCOM,

$$C_{ST} = \frac{1000 * Q_{ST}}{8760 * 15}\left(0.0002466 Q_{ST}^2 - 0.2243 Q_{ST} + 150.527\right)\$/\mathrm{H}$$
$$Q_{ST} = 0.0302\ \mathrm{MVAR}$$

Using the mathematical expressions given above, MATLAB codes are written for getting the solutions of this example as below.

```
%%% MATLAB codes for compensation cost through STATCOM
(ST)
>>clear all;
>>clc;
>>qst=0.0302;          % MVAr generated
% compensation cost through ST
>>cost_qst=((1000*qst)/(8760*15))*((0.0002466*qst*qst)-
(0.2243*qst)+150.527)
```

The results for the program given above are;
For MVAr generated = 0.0302 MVAR
Compensation cost through FC = 0.0346 \$ per H.

4 Reactive Power Compensation Scheme in Ihes

A block diagram for wind-diesel based IHES is given in Fig. 3. Self excited induction generator coupled with wind turbine, synchronous generator coupled with diesel genset, fixed capacitor and STATCOM as reactive power compensators and a load are connected in parallel to a common bus line to define an isolated hybrid electric system. Mathematically, under steady state,

$$\Delta P_L = \Delta P_{IG} + \Delta P_{SG} \tag{11}$$

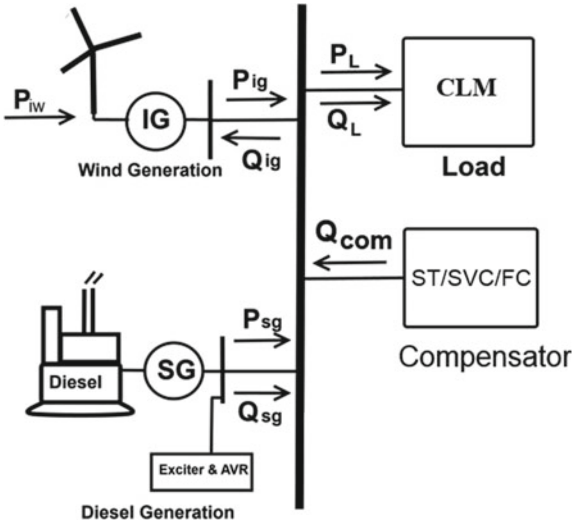

Fig. 3 Basic configuration of isolated hybrid power system with compensation schemes

$$\Delta Q_L + \Delta Q_{IG} = \Delta Q_{SG} + \Delta Q_{Com} \tag{12}$$

From Eqs. (11) and (12), it can be depicted that induction generator and synchronous generator both will manage for any change in the real power requirement and change in reactive power may occur due to demand of either induction generator or load or both together. As depicted in Eq. (12), this reactive power requirement may be supplied to IHES by either synchronous generator or compensator or both together. In present study, author is interested to investigate the cost of compensation through static and dynamic compensators only, so it is assumed that synchronous generator is generating only mandatory reactive power. The reactive power demand of system is fulfilled by compensators in response to change in system voltage when subjected to small disturbances.

In available studies, STATCOM alone was carried out for reactive power compensation in IHES due to the technical advantage of fast response of it. Although STATCOM has better compensation performance but it gives compensation at a very high cost. So, STATCOM as dynamic compensator alone does not give economic solution for voltage control in IHES. The compensation cost of fixed capacitor as static compensator is very low, but they alone are not capable of providing the adequate solution of voltage regulation. The compensation cost can be reduced by introducing static compensation with dynamic compensation on compromising with voltage response within permissible range. Hence, optimization technique is introduced in this chapter that provides economic solution of reactive power compensation for an isolated hybrid electric system.

Mathematically, total reactive power compensated by reactive power compensators is given as in Eq. (13). Since static and dynamic compensators both are being participated for reactive power compensation, this reactive power Q_{com} must be equal to the sum of reactive power generated by static compensator (FC) and dynamic compensator (ST) as represented in Eq. (14);

$$Q_{com} = Q_{IG} + Q_{Load} - Q_{SG} \tag{13}$$

$$Q_{com} = Q_{FC} + Q_{ST} \tag{14}$$

Since, a fast acting device is necessarily required for compensation so that system may reach its steady state with less settling time under dynamic conditions. Variable demand is satisfied by dynamic compensation i.e. STATCOM only while steady state fixed demand can be satisfied either by STATCOM alone or combination of fixed capacitor with STATCOM. Therefore, system total compensation at any instant of time is given by Eq. (15).

Therefore, mathematically,

$$Q_{com} = \left\{Q_{FC}^{ss} + Q_{ST}^{ss}\right\} + Q_{ST}^{ts} \tag{15}$$

In a restructured environment, in spite of the fact that the cost of reactive power may be dominantly linked with the price of active energy as well as other services, it is considered as an ancillary service which is priced separately. It is further assumed that isolated hybrid electrical system is designed by an independent supplier who used to decide participation of reactive power compensators on the basis of their cost, rating, and system voltage response. For cost analysis, compensation cost function is defined for fixed capacitor and STATCOM in succeeding sections. Equation (15) gives the participation of static and dynamic compensators during steady state and only dynamic compensator during dynamic condition. Total reactive power compensation must satisfy Eq. (13) always in system. Therefore, total compensation cost is formulated in Eq. (16) and it can be evaluated using the cost function of fixed capacitor and STATCOM. It is assumed that the cost of reactive power in system includes only the reactive power production cost of STATCOM and fixed capacitors as explained in preceding section.

$$C(Q_{com}) = \left\{C_{FC}\left(Q_{FC}^{ss}\right) + C_{ST}\left(Q_{ST}^{ss}\right)\right\} + C_{ST}\left(Q_{ST}^{ts}\right) \tag{16}$$

5 Simulink Model Representation for IHES

A basic block diagram of wind diesel based IHES is presented in Fig. 3. In this section, the transfer functions of each component, which are used to develop the simulink model for electrical system shown in Fig. 4, are presented in their corresponding subsections. The s-domain quantities/expressions are represented with the s symbol in parenthesis with quantity. This simulink model will support in developing the

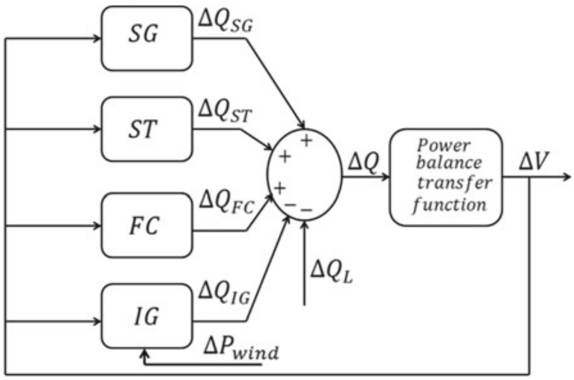

Fig. 4 Representation of voltage-reactive power balance equation in IHES

voltage and reactive power responses of the system component and these responses will be used in getting the optimal values reactive power with the help of available reactive power compensators. Since the study is being focussed for reactive power compensation and voltage control of the electrical system in this chapter. A reactive power balance equation given in Eq. (12) is taken for the study only and hence, simulink block diagram is developed for the transfer functions of change in reactive power with voltage for each component and for complete model.

5.1 Modelling for Reactive Power Balance in IHES

According to the energy policies and recommendations of international standard IEC 60038, the voltage permissible range at load end is ±10%; thus other devices connected in system should respond fast to achieve desirable voltage. This demand is maintained by releasing extra reactive power from synchronous generator, STATCOM and fixed capacitor. But, this disturbance will cause a voltage change due to which reactive power required by induction generator and load will also vary. The net reactive-power surplus,

$$\Delta Q = \Delta Q_{SG} + \Delta Q_{FC} + \Delta Q_{ST} - \Delta Q_{IG} - \Delta Q_{L} \quad (17)$$

The governing voltage reactive power balance equation for IHES is well established in Ref. [44] and presented in Eq. (18) below.

$$\Delta Q = \left(s\frac{V}{\omega X_m} + D_v \right) \Delta V \quad (18)$$

D_v is defined as the transfer function of change in reactive power with voltage change for load. The procedure for estimating this is explained in detail in Ref. [40]. Equations (17) and (18) can be clubbed to form a complete linear model of

IHES as shown in Fig. 4. For block diagram model represented in Fig. 3, system attains disturbances through load reactive power and wind input real power change. Figure 4 represents synchronous generator, STATCOM, fixed capacitor and induction generator as subsystem in IHES. As in Fig. 4, linear model of each subsystem is required for developing simulink model and therefore, linear model for all system components are discussed in succeeding subsections here.

5.2 Synchronous Generator Model Equations

Synchronous generator is the most popular diesel operated genset in small scale power generation. The synchronous generator is equipped with governor and exciter [5]. The exciter is a device which feeds dc supply to the main generator field. IEEE has proposed following standard models for representation of excitation systems for system studies.

1. Type 1 Excitation System—Continuously Acting Exciter And Regulator
2. Type 2 Excitation System–Rotating Rectifier System
3. Type 3 Excitation System—Static with Terminal Current and Potential Sources
4. Type 4 Excitation System—Non Continuous acting.

It is elaborated that IEEE excitation system of type-1 is the most popularly used excitation system with diesel genset and the same is used in this study too [45]. A linear model of synchronous generator with ΔV as input and ΔQ_{SG} as output is developed in Ref. [46] and is presented in Fig. 5.

The values of constants K_1, K_2, K_3 and K_4, shown in Fig. 5, are given in Eq. (19)–(22) from Ref. [40].

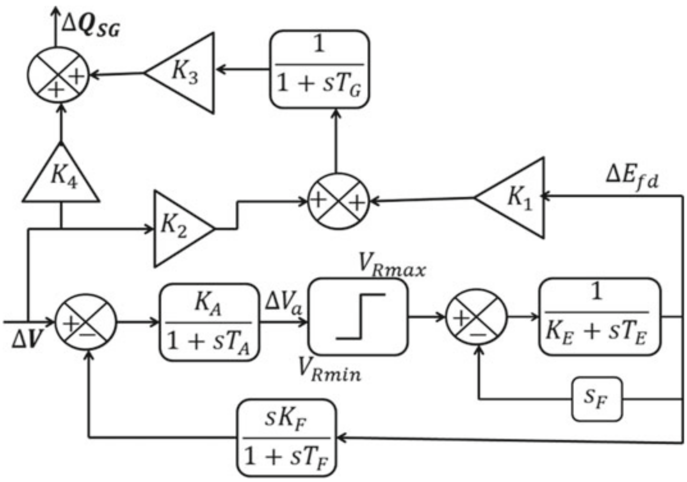

Fig. 5 Representation of linear model *of synchronous generator*

$$K_1 = \frac{X'_d}{X_d} \tag{19}$$

$$K_2 = \frac{\left(X_d - X'_d\right)}{X_d} \cos\delta \tag{20}$$

$$K_3 = \frac{V\cos\delta}{X'_d} \tag{21}$$

$$K_4 = \frac{E'_q\cos\delta - 2V}{X'_d} \tag{22}$$

The standard values of these parameters are chosen in model and are defined as in Ref. [47];

Voltage regulator gain constant; $\mathrm{K_A} = 40$
Voltage regulator time constant; $\mathrm{T_A} = 0.05$ s
Exciter gain constant; $\mathrm{K_E} = 1.0$
Exciter time constant; $\mathrm{T_E} = 0.5$ s
Stabilizing circuit gain constant; $\mathrm{K_F} = 0.5$
Stabilizing circuit time constant; $T_F = 0.75$ s
Saturation function; $S_F = 0$.

5.3 *Induction Generator Model Equations*

A linear model of induction generator is developed for approximate equivalent circuit of induction generator as shown in Fig. 6.

$$R_{eq} = R_s + R_r \tag{23}$$

$$X_{eq} = X_s + X_r \tag{24}$$

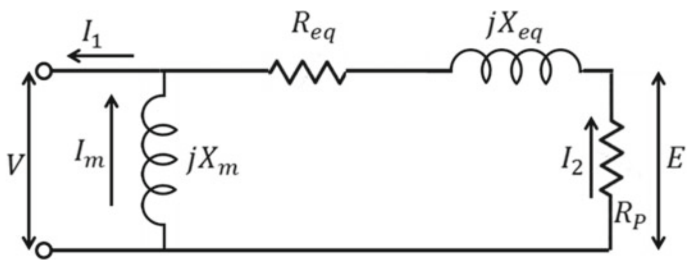

Fig. 6 Reduced approximate equivalent circuit for induction generator

$$R_y = R_P - R_{eq} \tag{25}$$

In Fig. 6, applying nodal analysis at R_P terminal

$$\frac{E - V}{R_{eq} + jX_{eq}} = \frac{E}{R_P} \tag{26}$$

On solving,

$$E = \left[\frac{R_P R_y}{R_y^2 + X_{eq}^2} + j \frac{R_P X_{eq}}{R_y^2 + X_{eq}^2} \right] V \tag{27}$$

Induction generator apparent power S_{ig} would be;

$$S_{ig} = V I_1^* \tag{28}$$

$$S_{ig} = V(I_2 + I_m)^* \tag{29}$$

$$S_{ig} = V I_2^* - V I_m^* \tag{30}$$

$$S_{ig} = V\left(\frac{E - V}{R_{eq} + jX_{eq}}\right)^* - V\left(\frac{V}{jX_m}\right)^* \tag{31}$$

Substituting values and solving for separating real and imaginary terms,

$$S_{ig} = \left[\frac{R_y}{R_y^2 + X_{eq}^2} V^2 \right] - j \left[\left\{ \frac{X_{eq}}{R_y^2 + X_{eq}^2} + \frac{1}{X_m} \right\} V^2 \right] \tag{32}$$

S_{ig} in Eq. (32) gives expression of total electric power generated by induction generator. Real part is the active power developed by induction generator. Since imaginary term of expression is negative in magnitude. This shows that the reactive power is absorbed by the induction generator. Also reactive power expression has two terms; first term denotes the power absorbed by induction generator and second term denotes the reactive power required for magnetization in induction generator.

The wind input power P_{wind} is given by,

$$P_{wind} = Re\{E I_2^*\} = Re\left\{ E \left(\frac{E - V}{R_{eq} + jX_{eq}} \right)^* \right\} \tag{33}$$

On solving,

$$P_{wind} = \frac{R_y}{R_y^2 + X_{eq}^2} V^2 \tag{34}$$

From Eq. (32), the reactive power which is absorbed by the induction generator

$$Q_{IG} = \frac{X_{eq}}{R_y^2 + X_{eq}^2} V^2 \tag{35}$$

Self Excited Induction generator may work under two basic conditions: operation of the wind energy conversion system (WECS) at constant speed or variable speed in terms of change in wind input real power.

In the case of constant speed/slip operation Eq. (32) can be rewritten in s plane as,

$$\Delta Q_{IG} = \frac{2VX_{eq}}{R_y^2 + X_{eq}^2} \Delta V \tag{36}$$

$$K_5 = \frac{2VX_{eq}}{R_y^2 + X_{eq}^2} \tag{37}$$

$$\Delta Q_{IG} = K_5 \Delta V \tag{38}$$

If the induction generator is operating for variable speed/slip then the term R_y is not constant and its value will depend on the slip. Therefore, the expression for the reactive power will not depend only on the voltage but also on the input power available at blade of the induction generator. Solving for small perturbation in the case of variable speed/slip operation, the equation can be written in s plane as [48],

$$\Delta Q_{IG}(s) = K_6 \Delta P_{wind}(s) + K_7 \Delta V(s) \tag{39}$$

$$K_6 = \frac{X_{eq}}{R_P - \left\{ \left(R_y^2 + X_{eq}^2 \right) / 2R_y \right\}} \tag{40}$$

$$K_7 = \frac{2V}{R_y^2 + X_{eq}^2} \left[X_{eq} - \frac{R_P X_{eq}}{R_P - \left\{ \left(R_y^2 + X_{eq}^2 \right) / 2R_y^2 \right\}} \right] \tag{41}$$

Equations (38) and (39) represent expressions for linear model of induction generator. These expressions have been developed for constant and variable speed respectively as shown in Fig. 7a, b. For IHES in this chapter, variable speed model of induction generator is used.

5.4 Fixed Capacitor Model Equations

Reactive power and voltage relation for fixed capacitor is a well established one. Equation (42) provides design information about capacitance per phase in the system. Change in reactive power of fixed capacitor with voltage variation is given in Eq. (43)

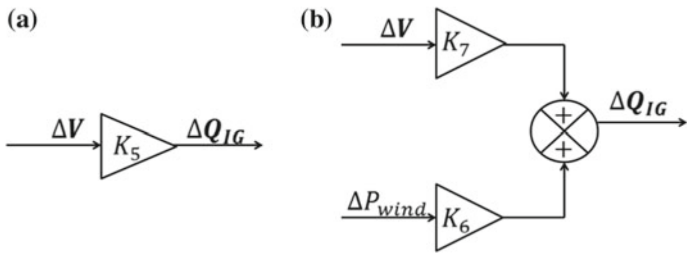

Fig. 7 Linear model for **a** constant slip and **b** variable slip model of induction generator

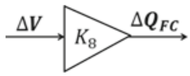

Fig. 8 Linear model for fixed capacitor

for small perturbation. Linear model for fixed capacitor is represented in Fig. 8 [46].

$$Q_{FC} = \frac{V^2}{X_C} \tag{42}$$

$$\Delta Q_{FC}(s) = K_8 \Delta V(s) \tag{43}$$

$$K_8 = \frac{2V}{X_C} \tag{44}$$

5.5 STATCOM Model Equations

STATCOM controls the reactive current flow by adjusting firing angles of thyristor for suitable control of the inverter voltage with respect to the bus voltage and finally, STATCOM controls reactive power generation or absorption in system. For the power flow modelling of the STATCOM, the reactive power expression is given in Eq. (45) [21],

$$Q_{ST} = (kV_{dc})^2 B_{ST} - kV_{dc} V B_{ST} \cos\alpha \tag{45}$$

STATCOM reactive power depends upon two main variables V and α. Based on the Eq. (45), the linear STATCOM equation for small disturbance is given below [44],

$$\Delta Q_{ST}(s) = K_{11} \Delta\alpha(s) + K_{12} \Delta V(s) \tag{46}$$

where,

$$K_{11} = kV_{dc}VB_{ST}\text{Sin}\alpha \tag{47}$$

$$K_{12} = -kV_{dc}B_{ST}\text{Cos}\alpha \tag{48}$$

The small signal models of STATCOM used in dynamic analysis can be designed using three blocks namely regulator, thyristor firing delay and phase sequence delay [49]. A proportional integral controller based linear model STATCOM are given in Fig. 9.

Example 3 Find the cost of loss, mandatory and reserve reactive power for 111 kVA, 400 V, 50 Hz synchronous generator having 0.9 lagging power factor following parameters are specified,

$$\begin{array}{ll} R_a = 0.002 & \mathrm{K_A} = 40 \\ X'_d = 0.15 & \mathrm{T_A} = 0.05\,\mathrm{s} \\ X_d = 1 & \mathrm{K_E} = 1.0 \\ T'_{d0} = 5 & \mathrm{T_E} = 0.5\,\mathrm{s} \\ X_q = 1 & \mathrm{K_F} = 0.5 \\ X_s = 1 & T_F = 0.75\,\mathrm{s} \\ X'_s = 0.15 & \end{array}$$

Solution From the given parameters,

$$S_{SG} = 111\,\text{kVA}$$

$$\text{Cos}\,\theta_{SG} = 0.9$$

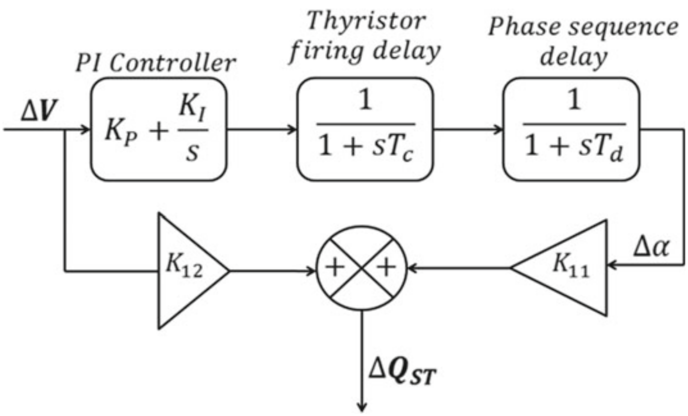

Fig. 9 Linear model of STATCOM

$$P_{SG} = S_{SG}\text{Cos}\,\theta_{SG} = 100\,\text{kW}$$

Let base power and base voltage as given below,

$$P_{SG,Base} = 100$$

$$V_{SG,Base} = 400$$

So,

$$P_{SG,pu} = 1$$

$$V_{SG,pu} = 1$$

Mandatory reactive power can be calculated as,

$$Q_{mandatory} = P_{SG,pu}\tan\theta_{SG}$$

For estimative cost of loss reactive power solve the expression for getting the value of $Q_{SG,pu}$,

$$P_{SG,pu}^2 + \left(Q_{SG,pu} + \frac{3V^2}{X_s}\right)^2 = \left(\frac{3VE_q}{X_s}\right)^2$$

$$Q_{cost\,of\,loss} = Q_{SG,pu}$$

$$Q_{reserve} = Q_{cost\,of\,loss} - Q_{mandatory}$$

Using the mathematical expressions given above, MATLAB codes are written for getting the solutions of this example as below.

```
%%% MATLAB codes for cost of loss, mandatory and re-
serve reactive power for SG
clear all
clc
vb=400;
xs=1;
xq=1;
ra=0.002;
psgbase=100;
sgpf=0.9; % lagging power factor (LPF)
v=complex(400,0); % volatge in polar form
vpu=abs(v)/vb; % per unit line voltage
psg=100;          % kW of SG
psgpu= psg/psgbase; % per unit kW power
phi=acosd(sgpf); % phase angle
ia=psgpu/(sqrt(3)*vpu*cosd(phi));
jayee=atand(((vpu*sind(phi))+(ia*xq))/((vpu*cosd(phi))+
(ia*ra)));
delta=jayee-phi;
iasg=complex(ia*cosd(phi),ia*sind(-1*phi));
eq_complex=(vpu+1i*0)+(iasg*complex(0,xs));
eq=abs(eq_complex);
qsgpu=psgpu*tand(phi); % per unit reactive power of SG
q_mandatory=qsgpu;
f1=psgpu^2;
f2=3*vpu*vpu/xs;
f3=(3*vpu*eq/xs)^2;
syms x;
y=((f1)+(x+(f2)).^2-f3);  %  formula  from  field  current
limit of SG
z=double(solve(y));
if z(1,1)>=0
 z=z(1,1);
end
 if z(2,1)>=0
 z=z(2,1);
 end
q_cost_of_loss=z;
q_reserve=q_cost_of_loss-q_mandatory;
% per phase actual value
q_cost_of_loss=(q_cost_of_loss/3)*psgbase
q_mandatory=(q_mandatory/3)*psgbase
q_reserve=(q_reserve/3)*psgbase
```

The results for the above given MATLAB program are,
$Q_{mandatory} = 16.1441$ kVAR per phase
$Q_{cost\ of\ loss} = 36.3693$ kVAR per phase
$Q_{reserve} = 20.2252$ kVAR per phase.

Example 4 For developing the linear model of synchronous generator as shown in Fig. 5, evaluate the constants K_1, K_2, K_3 and K_4 with the help of synchronous generator parameters as given in previous Example 3.

Solution All the parameters given in Example 3 are used to find the value of constants K_1, K_2, K_3 and K_4. All these constant are being calculated in per unit quantities and the base power and base voltage for these calculations is being assumed equal to SG rating. Therefore, MATLAB codes are written for getting the solutions of this example as below.

```
%%% MATLAB codes for evaluating the value of constants
K1, K2, K3 and K4
clear all;
clc;
%input data for system design (all powers are kW, kVAR)
v=complex(400,0); vpu=1;
psg=100;
psg_base=100;
sgpf=0.9;
phi=acosd(sgpf);
qsg=psg*tand(phi);
psgpu=psg/psg_base;
ra=0.002;
xd_dash=0.15; xd=1;
tdo_dash=5;
xq=1;
xs=1;
xs_dash=0.15;
ke=1;
te=0.5;
ka=40;
ta=0.05;
kf=0.5;
tf=0.75;

%%%% SG model constants calculation for simulink model
zsg=1;                   % per unit impedance of SG
ia=(psg/psg_base)/(sqrt(3)*vpu*cosd(phi));
za-
yee=atand(((vpu*sind(phi))+(ia*xq*zsg))/((vpu*cosd(phi)
)+(ia*ra*zsg)));
delta=zayee-phi;
iasg=complex(ia*cosd(phi),ia*sind(-1*phi));
eq_complex=(vpu)+(iasg*(1i*xs*zsg));
eq=abs(eq_complex);
```

```
id=(eq-(vpu*cosd(delta)))/(xd*zsg);
eq_dash=eq-((xd-xd_dash)*zsg*id);
tg=(tdo_dash*(xd_dash*zsg)/(xd*zsg));
k1=(xd_dash*zsg)/(xd*zsg)
k2=(xd-xd_dash)*zsg*cosd(delta)/(xd*zsg)
k3=vpu*cosd(delta)/(xd_dash*zsg)
k4=((eq_dash*cosd(delta))-(2*vpu))/(xd_dash*zsg)
```

The results for the above given MATLAB program are,

$$K_1 = 0.15$$
$$K_2 = 0.775$$
$$K_3 = 6.0787$$
$$K_4 = -7.3421$$

Example 5 Calculate the full load and no load reactive power requirement for the induction generator with following specifications; $V = 400$ V, $P_{IG} = 150$ kW, $\text{Cos}\,\theta_{IG} = 0.9$, $P = 2$, $s = 0.04$, $f = 50$, $\eta = 90\%$. Consider line voltage as base voltage and real power of generator as base power.

Solution The calculations are being done for the equivalent circuit diagram of induction generator as given in Fig. 6. Most of the mathematical expressions used for the calculation purposes in writing MATLAB codes are imported from the Ref. [50]. For better understanding of the codes readers are suggested to read this paper.

```
%%% MATLAB codes for evaluating the reactive power re-
quirement for the induction generator
clear all;
clc;
%%%% base values for pu calculation
vb=400;      % Base voltage
sigb=150;          % Base power
zig_base=(vb*vb)/(sigb*1000); % Base impedance
%input data for system design
v=complex(400,0); vpu=1;
pig=150;          igpf=0.9;          theta=acosd(igpf);
qig=pig*tand(theta);
f=50; pole=2; s=0.04; eff=0.9; p_mech=(pig*eff);
%%%%% IG equivalent circuit parameters
i1=(pig*10^3)/(sqrt(3)*abs(v)*igpf); % for current re-
fer equivalent circuit of IG
I1=complex(i1*cosd(theta),i1*sind(-theta));
```

```
zeq=(abs(v)/sqrt(3))/I1;
zeq_complex=zeq*cosd(theta)+1i*zeq*sind(theta);
im_zeq=imag(zeq_complex);
sigma=(1-igpf)/(1+igpf);
xm=(abs(v)/sqrt(3))/(abs(I1)*sqrt(sigma));
Xm=complex(0,xm);
Im=((v)/sqrt(3))/Xm;
I2=I1-Im;                % -1 multiplied with I1 as it
is generator
i2=abs(I2);
Rp=(p_mech*10^3)/(3*i2*i2);
r=Rp*s/(1-s);
req=2*r;
rsum=req+Rp;
ry=Rp-req;
syms xeq
Nr=(rsum*rsum*xm)+(xeq*xm*(xeq+xm));
Dr=(rsum^2)+(xeq+xm)^2;
form_x=im_zeq-(Nr/Dr);
z=double(solve(form_x));
a=z(1,1);
b=z(2,1);
if a>=0
 z=a;
end
if b>=0
 z=b;
end
xeq=z;
x=xeq/2;
% converting parameters in pu values
xeq=xeq/zig_base;
x=x/zig_base;
req=req/zig_base;
r=r/zig_base;
xm=xm/zig_base;
Rp=Rp/zig_base;
ry=ry/zig_base;
%%%% no load and full load current of IG
io=(vpu/sqrt(3))/(1i*xm);
i2=(vpu/sqrt(3))/(req+Rp+1i*xeq);
io=abs(io);
i2=abs(i2);
% per unit values of full load and no load reactive
power of IG
```

Therefore, the results for the above given MATLAB program are,

Full load reactive power requirement for the induction generator = 38.4334 kVAR per phase.

No load reactive power requirement for the induction generator 14.9368 kVAR per phase.

Example 6 For developing the linear models of induction generator as shown in Fig. 7, evaluate the constants K_5, K_6 and K_7 with the help of induction generator as specified in previous Example 5. Also calculate the wind input power by neglecting the constant losses.

Solution MATLAB codes given in Example 5 are followed up to the estimation of equivalent circuit parameters i.e. (from line "clear all" to "ry = ry/zig_base;"). The continuation command to this for evaluating the constants K_5, K_6 and K_7 are summarized below in the solution. All these constant are being calculated in per unit quantities and the base power and base voltage for these calculations is being assumed equal to IG rating. All the mathematical expression used in writing MATLAB codes are imported from the Sect. 5.3. Therefore, MATLAB codes are written for getting the solutions of this example as below.

```
qig_fl=(io^2*xm)+(i2^2*xeq);
qig_nl=(io^2*(xm+xeq));
% actual values of full load and no load reactive power
of IG
qig_fl=qig_fl*sigb
qig_nl=qig_nl*sigb

%%% MATLAB codes for evaluating the value of constants
K5, K6 and K7 and input wind power
% copy the program of example 13.5 just before writing
the codes given below
% pu parameters at IG base
xeq=xeq/zig_base;
x=x/zig_base;
req=req/zig_base;
r=r/zig_base;
xm=xm/zig_base;
Rp=Rp/zig_base;
ry=ry/zig_base;
Pwind=Rp*vpu^2/(ry^2+xeq^2);
Pconstantloss=0;
Piw=(Pwind+Pconstantloss)                          % input
wind power estimation
k5=2*vpu*xeq/(ry^2+xeq^2)
k6=xeq/(Rp-((ry^2+xeq^2)/(2*ry)))
k7=(2*vpu/(ry^2+xeq^2))*(xeq-(Rp*xeq/(Rp-

((ry^2+xeq^2)/(2*ry)))))
```

Therefore, the results for the above given MATLAB program can be summarized as,

$$\text{Wind input power to induction generator} = 0.7996\,\text{pu}$$

$$K_5 = 1.2617$$

$$K_6 = 3.9024$$

$$K_7 = -4.9792$$

Example 7 A single unit wind and single unit diesel generator are coupled together to develop an isolated hybrid electrical system. If induction generator and synchronous generator are used for wind driven power generator and diesel driven power generator respectively. A 200 kW at 0.9 lagging power factor load is being supplied by this IHES in which IG and SG are used for supplying power 150 kW at 0.9 lagging power factor and 250 kW at 0.9 lagging power factor respectively. Other specifications for SG and IG are same as in Example 3 and 5 respectively. Calculate the reactive power requirement through reactive power compensator assuming that SG is generating only mandatory reactive power.

Solution This example is designed to understand the reactive power balance for IHES during steady state conditions. For the operation of this IHES, reactive power is required for load and IG which can be supplied by synchronous generator. But it has been cleared in the problem that SG will generate only the amount of reactive power equal to mandatory reactive power. So, rest reactive power requirement can only be fulfilled by any compensator. Mathematically,

$$Q_{com} = Q_L + Q_{IG} - Q_{SG}$$

Q_{SG} is the mandatory reactive power which has been obtained in Example 3. Q_{IG} is the full load reactive power requirement of induction generator that has already been evaluated in Example 5.

$$Q_{SG} = 16.1441\ \text{kVAR per phase}$$

$$Q_{IG} = 38.4334\ \text{kVAR per phase}$$

$$Q_L = \frac{P_L \tan\left(\cos^{-1}(load\ power\ factor)\right)}{3} = 32.2881\ \text{kVAR per phase}$$

Therefore,

$$Q_{com} = 62.6495\ \text{kVAR per phase}$$

Example 8 Repeat the Example 7 and find the per unit value of reactive power from compensator for load 250 kW at 0.9 lagging power factor.

Solution To keep all the quantities at the same base, load power is taken as base power.

```
%%% MATLAB codes for evaluating the per unit value of
reactive power from compensator
clear all
clc
sbase=250;
qsg=16.1441/sbase; % As obtained in example 13.3
qig=38.4334/sbase; % As obtained in example 13.5
pl=250/(3*sbase);
lpf=0.9;
ql=pl*tand(acosd(lpf))
qcom=ql+qig-qsg
```

Therefore, the results for the above given MATLAB program can be summarized as,

$$\text{Reactive power required from compensator} = 0.2506\,\text{pu kVAR per phase}$$

Example 9 Consider a 250 kW, 0.9 lagging power factor exponential type static load is connected with the IHES as explained in Example 7. If the exponential factor for static load is 3, find the transfer function D_v for this load as in Eq. (18).

Solution The detail explanation for obtaining the transfer function of exponential type static load function is beyond the scope of this chapter. In Ref. [50], the detail documentation for obtaining it is well presented and the same is being used here.

```
%%% MATLAB codes for evaluating transfer function of
exponential type static load function
clear all
clc
lpf=0.9;
vpu=1;              % base voltage
Pl=250/3;            % per phase load power
s_base=250;                % base power
q=3;          % exponential factor
Ql=Pl*tand(acosd(lpf));
Ql_pu=Ql/s_base;
num=q*Ql_pu;
den=vpu;
TFsl=tf(num,den)  % estimation of Dv as in ref. [51]
```

Therefore, the results for the above given MATLAB program can be summarized as,

$$\text{Load transfer function } D_v = 0.4843$$

Example 10 If reactive power required in Example 8 through reactive power compensator is given by fixed capacitor only, evaluate the constant K_8 for FC as shown in Fig. 8.

Solution Reactive power required from compensator is 0.2506 pu kVAR per phase. If the same reactive power is supplied through FC only at voltage 1.0 pu, the constant K_8 can be evaluated as $K_8 = \frac{2V}{X_C}$, where capacitive reactance per phase can be defined as $X_C = \frac{V^2}{Q_{FC}}$. It is assumed that capacitor bank is delta connected so phase voltage is same as line voltage.

```
%%% MATLAB codes for evaluating constant k8 for FC
clear all
clc
v=1;
qfc=0.2506;
xc=v^2/qfc
k8=2*v/xc
```

Therefore, the results for the above given MATLAB program can be summarized as,

Capacitive reactance per phase, $X_C = 3.9904$ pu ohm

$$K_8 = 0.5012$$

Example 11 Repeat the Example 10, if reactive power required through reactive power compensator is given by STATCOM only. Evaluate the constants K_{11} and K_{12} for STATCOM as shown in Fig. 9.

Solution For the power flow modelling of the STATCOM, the reactive power expression is given in Eq. (45).

$$Q_{ST} = (kV_{dc})^2 B_{ST} - kV_{dc} V B_{ST} \cos\alpha$$

STATCOM constants K_{11} and K_{12} can be expressed as in Eqs. (47) and (48). The required variable for STATCOM has been evaluated by the author in Ref. [44]. The same methodology is being followed for evaluating these parameters in this example and the corresponding expressions are imported in MATLAB codes as given below.

```
%%% MATLAB codes for evaluating constant k11 and k12
for ST
clear all
clc
p=12; % Number of pulses
vpu=1;
a_st=1.2; % modulation index for ST
fs=10e3; % Switching frequency for ST
f=50;
qst=0.2506; % Reactive power requirement
m=p*sqrt(6)/(6*pi);
k=1/m;
vac=vpu;
vdc=vac/k;
is=(qst)/(sqrt(3)*vac);
icr=(5/100)*(2*sqrt(2)*is);
lac=(sqrt(2)*vac/(6*a_st*fs*icr));
B=1/(2*pi*f*lac);
alpha=acosd(((k*vdc)^2*B-(qst))/(k*vdc*vac*B));
k11=k*vdc*vac*B*sind(alpha)
k12=-(k*vdc*B*cosd(alpha))
```

Therefore, the results for the above given MATLAB program can be summarized as,

$$K_{11} = 1.2646$$

$$K_{12} = -3.0653$$

6 Importance of Dynamic Compensator for Voltage Control

For IHES showing in Fig. 3, steady state reactive power can be generated for IHES either by static or by dynamic compensator as depicted by two Examples 10 and 11. Equation (15) explains that dynamic condition reactive power requirement cannot be generated by static compensator. To verify this statement and to check any feasibility of using single static compensators for dynamic changes, only fixed capacitor is connected as reactive power compensator. A simulink model is developed in MATLAB simulink toolbox window for the IHES components as shown in Fig. 4 except the STATCOM block. All the constants and parameters are well estimated in the preceding examples of this chapter. For analyzing the FC behaviour for dynamic conditions, a 10% step disturbances are given at t = 1 s in input power and load.

Figure 10 clearly demonstrates how the voltage collapse in presence of FC as

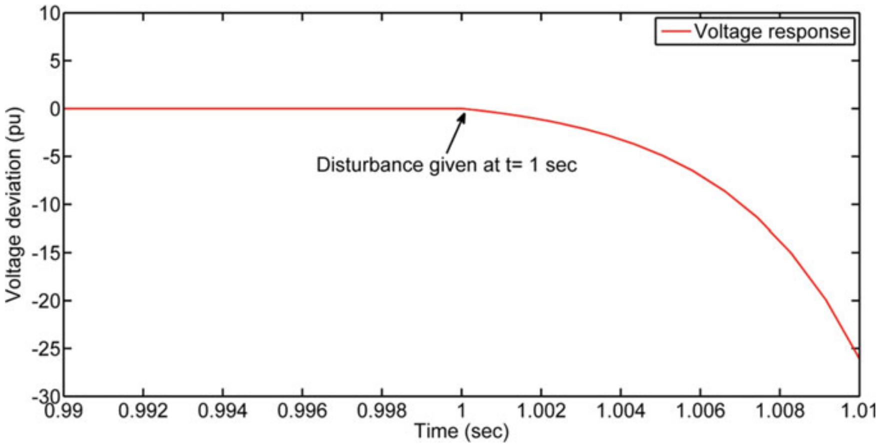

Fig. 10 Voltage collapse for load pattern 1 in presence of static compensator only

only compensator for IHES at t = 1 s. Till t = 1 s IHES demands only steady state reactive power that can easily be supplied by FC. But, as soon as the disturbances occur in IHES at t = 1 s, FC alone is not capable to support the system for this dynamic compensation requirement. On the other side, if cost of compensation is not a constraint for adopting reactive power compensation method, STATCOM can alone be used for providing reactive power compensator. A complete simulink diagram for IHES with ST only as reactive power compensator is presented in Fig. 11.

7 Optimization of Reactive Power Participation

It can be calculated from preceding section that optimized participation of both static compensator (FC) and dynamic compensator (ST) can be used to get technically and economically accepted solution of voltage control for any IHES. A method for getting optimum participations of reactive power compensation is proposed in this section with the help of Fig. 12 in which FC and ST are being connected for supplying reactive power for IG and Load in presence of SG.

It has already been discussed that cost of fixed capacitor is very low compare to STATCOM but fixed capacitors do not respond for system under dynamics conditions. STATCOM alone can provide an adequate solution of reactive power compensation for system voltage control but it makes system very costly. For dynamic conditions, reactive power can only be generated through fast acting dynamic compensating device but steady state reactive power requirement can be planned through participation of static as well as dynamic compensators so that overall compensation cost may be reduced. The role of static compensation deforms the voltage response

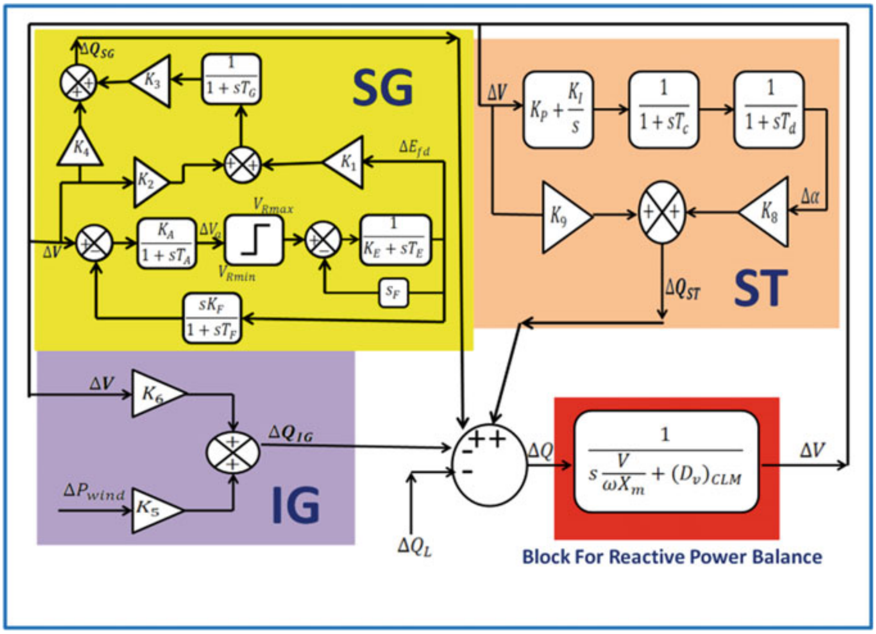

Fig. 11 Simulink model for IHPS with SG, IG, ST and CLM

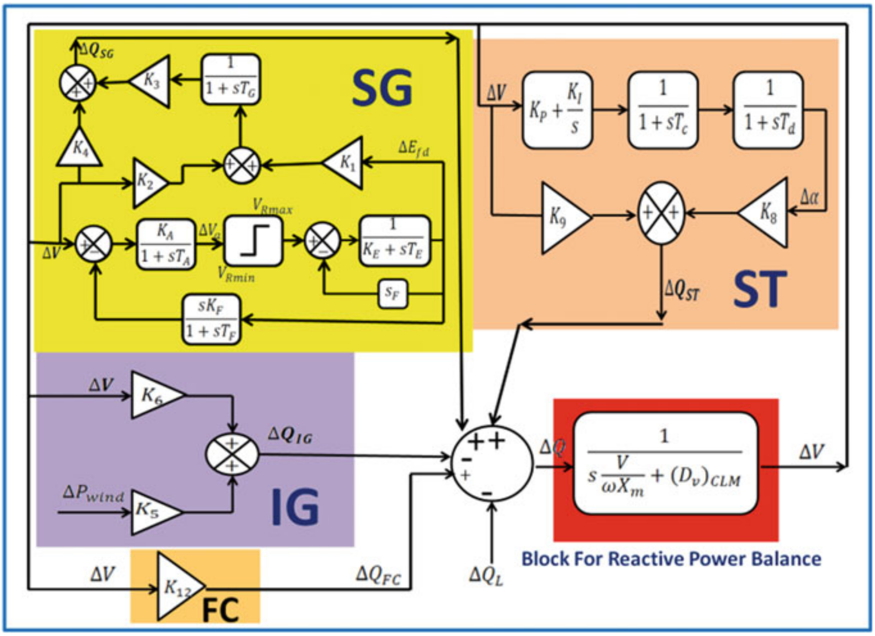

Fig. 12 Simulink block diagram with static and dynamic reactive power compensator

of the system and hence participation of fixed capacitor with STATCOM should be optimized up to the extent of voltage variations within the permissible range.

Therefore, an optimization problem is formulated for reactive power participation using static and dynamic compensators in system but considering two important aspects;

1. Minimizing the cost of compensation under steady state through participation of fixed capacitor as static compensator along with STATCOM as dynamic compensator, and
2. Participation of static compensator with dynamic compensation up to the extent where system voltage responses remain in its pre defined acceptable range.

The proposed approach allows minimizing cost function given in Eq. (16). As discussed earlier, dynamic state reactive power is supplied by STATCOM only therefore term $C_{ST}\left(Q_{ST}^{ts}\right)$ does not require to add in optimization problem. Therefore, an objective function J which represents cost function of reactive power compensation as in Eq. (49) is optimized to find best solution of reactive power compensation in the system. Functions of cost for STATCOM and fixed capacitor depend upon the reactive power released by them;

Objective function

$$J = C_{FC}\left(Q_{FC}^{ss}\right) + C_{ST}\left(Q_{ST}^{ss}\right) \tag{49}$$

Dynamic equations of fixed capacitor and STATCOM are represented by Eqs. (9) and (10). Their corresponding linear models as given in Figs. 8 and 9 are used in system's simulink model as in Fig. 4. This simulink model is used to find voltage response of system and reactive power responses for all system components in presence of both static and dynamic reactive power compensator together. Voltage responses for different participations between fixed capacitor and STATCOM can be tracked and used to decide the final acceptable system response.

Mathematically, reactive power must remain balance in the system and corresponding expressions for equality constraints can be written as;

Equality constraints

$$Q_{demand} = Q_{release} \tag{50}$$

$$Q_{demand} = Q_{IG} + Q_L - Q_{ST} \tag{51}$$

$$Q_{release} = Q_{FC}^{ss} + Q_{ST}^{ss} \tag{52}$$

Equation (52) explains that steady state reactive power is fulfilled by fixed capacitor and STATCOM. Optimized value of reactive power through STATCOM and fixed capacitor will be chosen with pre-acceptable range of voltage response. Reactive power released by STATCOM and fixed capacitors must be within the range as in Eqs. (53) and (54). Equations (55) and (56) define pre-acceptable range of voltage response for the system.

Inequality constraints

$$0 \leq Q_{ST}^{ss} \leq Q_{demand} \tag{53}$$

$$0 \leq Q_{FC}^{ss} \leq Q_{demand} \tag{54}$$

$$V_{min} \leq \Delta V \leq V_{max} \tag{55}$$

$$settling\, time \leq settling\, time_{acceptable} \tag{56}$$

Stability constraints
System voltage deviates due to load and input disturbances from its steady state value. The voltage deviation should reach to zero as earliest by the additional reactive power generation by the static and dynamic compensators. In other words, system should remain stable.

Acceptable range of voltage response should be decided first as described in Eqs. (55) and (56). Previously available papers suggest use of STATCOM only for reactive power compensation in isolated hybrid power system. In this work, optimum values of static and dynamic compensators are obtained. Therefore, two cases can be defined for comparative study of compensation cost analysis.

- Case I: STATCOM alone is used for reactive power compensation in the system.
- Case II: Participation of both fixed capacitor and STATCOM is used for reactive power compensation in the system.

To find the participation of compensators for getting system voltage response within the predefined acceptable range, a reference voltage is required. Though, this decision must be based on mutual acceptance of power quality between end user and electricity producers (private investors) in terms of system voltage quality. In this optimizing problem, characteristic parameters from voltage response are obtained in case I and these are used as a reference for deciding acceptable range of parameters for case II.

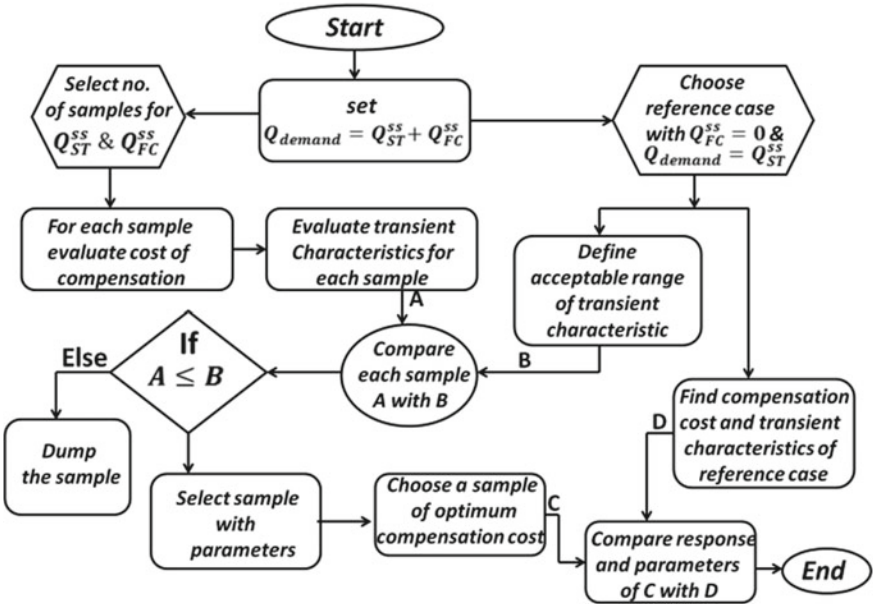

Fig. 13 Flow chart for reactive power compensation cost determination

For deciding the optimize participation of static and dynamic compensators, number of samples for reactive power generation from fixed capacitor and STATCOM are developed satisfying Eq. (52) by gradually increasing reactive power generation through fixed capacitor and decreasing reactive power generation through STATCOM.

For each sample, system voltage response is tracked and compared with predefined values and finally, reactive power participation is selected for optimum value of compensation cost. A flowchart showing algorithm for proposed optimization of compensation cost is presented in Fig. 13.

Example 12 Develop a simulink block diagram for an IHES with 150 kW IG and 100 kW SG. Plot the voltage response for the system if 10% step disturbance occurs in connected load of rating 250 kW and wind input power. Other ratings and specifications are same as in preceding examples.

Solution Figure 4 represents the complete simulink diagram for IHES. This simulink diagram is developed on MATLAB simulink model window with the help of required constants that are developed as in preceding examples. It should be noted that all the constants and parameters must be estimated on a common base values and therefore load values of voltage and power is taken as base power now. The constant are;

$k_1 = 0.1500$; $k_2 = 0.7750$; $k_3 = 2.4315$; $k_4 = -2.9368$; $k_5 = 0.7570$; $k_6 = 3.9024$; $k_7 = -2.9875$; $k_{11} = 1.2646$; $k_{12} = -3.0653$

A 10% step disturbances in wind input power and load reactive power is produced in simulink model with the help of source block parameter from the simulink library browser. STATCOM block diagram represented in Fig. 9 demonstrates regulator block. In Ref. [44], complete detail of STATCOM is given and same is used here. PI controller is used as regulator and the value of constants can be estimated using ISE criterion [51]. Algorithm to develop voltage response can be summarized as follows;

1. Develop reactive power required form STATCOM after evaluating the reactive power for SG, IG, and Load as in Examples 3, 5 and 7.
2. Evaluate gain constants for SG as estimated in Example 4.
3. Evaluate gain constants for IG as estimated in Example 6.
4. Evaluate gain constants for ST as estimated in Example 11.
5. Develop the constants for reactive power balance equation as given in Eq. (18).
6. Club all the IHES components together as presented in Fig. 4 at MATLAB simulink model window.
7. Define input wind power and load disturbance in simulink model disturbances.
8. Estimate the PI controller gain constants for STATCOM linear model.
9. Run the MATLAB codes having all the above discussed information. Simulink model is called in this MATLAB program and all the required information can be imported to simulink model through MATLAB codes.
10. Develop the required responses for the IHES like voltage response etc.

Figure 14 explains the voltage response for IHES when only STATCOM is used for supplying reactive power compensation. Due to disturbances at time 1 s, voltage starts to deviate and demand additional reactive power from the system to stabilize

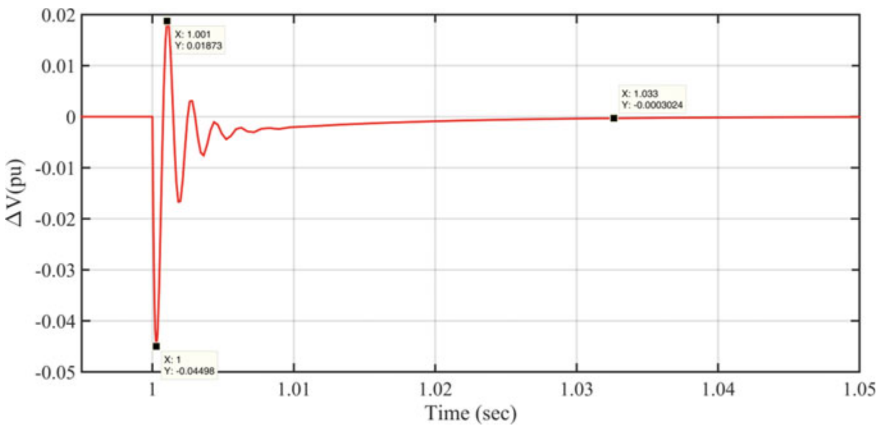

Fig. 14 Voltage response for ST as reactive power compensator

the system voltage. To control the voltage STATCOM starts acting and generate additional required reactive power to control the voltage. The maximum voltage deviation is 0.01873 pu and minimum deviation is −0.04498 pu while system voltage steles down at time 1.033 s.

Example 13 Find the reactive power compensation cost for IHES in Example 12.

Solution The expression for compensation cost through STATCOM,

$$C_{ST} = \frac{1000 * Q_{ST}}{8760 * 15}\left(0.0002466 Q_{ST}^2 - 0.2243 Q_{ST} + 150.527\right)\$/\mathrm{H}$$

$$Q_{ST} = 0.2506 \text{ pu MVAR}$$

Using the mathematical expressions given above, MATLAB codes are written for getting the solutions of this example as below.

```
%%% MATLAB codes for compensation cost through STATCOM
(ST)
>>clear all;
>>clc;
>>Q_st=0.2506;          % pu MVAr generated
>> pl_base =250;
% compensation cost through ST by converting pu in MVAR
>>cost_Qst_ref=(1000.*(Q_st.*pl_base./1000)./(8760.*15)
).*((0.0002466.*Q_st.*Q_st)-(0.2243.*Q_st)+150.527)
```

The results for the program given above are;

$$\text{Compensation cost through ST} = 0.0717\ \$\ \textit{per}\ \mathrm{H}$$

Example 14 For the voltage response developed in Example 12, find the transient parameters such as voltage dip, voltage rise and rise time.

Solution For the voltage response developed in Example 12, transient parameters can be evaluated by using the MATLAB codes as written below;

```
% evalaution of the transient parameters for the known
voltage response
sim('NAME_OF_MDL_FILE_STORED') % Syntax for running the
simulink model form MATLAB code
% From volatge response stored in workspace of simulink
model, time and volatge array can be seperated as
plot_t=sim_v.time;
plot_v=sim_v.signals.values;
% Reference voltage parametrs can be evaluated by these
two commands
V_par1=lsiminfo(plot_v,plot_t)
V_par2=stepinfo(plot_v,plot_t)
% syntax to get all parametrs saprately
V_data11=struct2cell(V_par1)
V_data1=cell2mat(V_data11)
V_data22=struct2cell(V_par2)
V_data2=cell2mat(V_data22)
Settlingtime=V_data1(1)
Voltagedip=V_data1(2)
Voltagerise=V_data1(4)
Risetime=V_data2(1)
```

Therefore, the results for the above given MATLAB program can be summarized as,

$$\text{Settling time} = 1.0199\,\text{s}$$
$$\text{Voltages dip} = -0.0450\,\text{pu}$$
$$\text{Voltage rise} = 0.0187\,\text{pu}$$

Example 15 Consider the settling time, voltage dip and voltage rise obtained in Example 14 as a reference parameters. Define the predefined acceptable range of voltage response (i.e. inequality constraints) for optimization procedure.

Solution Energy policies and recommendations of international standard IEC 60038, the voltage permissible range at load end is ±10%. Voltage response produced for IHES through STATCOM only as a reactive power compensator is assumed as reference response for achieving optimization participation of FC and ST. Therefore,

Reference value for voltage dip = −0.0450 pu
Reference value for voltage rise = 0.0187 pu
Reference value for settling time = 1.0199 s

The predefined acceptable range of voltage response (i.e. inequlity constraints) for optimization procedure is assumed to be,

Acceptable voltage rise ⇐ voltage rise + 0.05
Acceptable voltage dip ⇐ |voltage dip| + 0.05
Acceptable voltage settling time ⇐ settling time + 0.01

Example 16 Find the optimized participation for reactive power compensation using FC along with ST for this IHES keeping voltage control in its predefined acceptable range.

Solution In Example 13, compensation cost is given when ST is only used for reactive power compensation. Example 14 provides the voltage response transient parameters for the Fig. 14 given as the solution of Example 12. As explained earlier that dynamic condition requirement can only be given by ST only while to reduce the compensation cost FC can be introduced with ST for fulfilling the steady state reactive power demand. To make a technical acceptable solution for participations of static and dynamic compensator together, an acceptable solution should be decided first. The acceptable range of voltage response (i.e. inequality constraints) for optimization procedure is estimated in Example 15. Equality constraint for optimization problem is that total reactive power requirement should be the sum of reactive power from FC and reactive power from ST. Procedure for getting the optimized solution of compensation cost is defined through flow chart given in Fig. 13. A MATLAB code is developed in which numbers of samples are generated by increasing the reactive power from FC gradually and decreasing the reactive power from ST gradually keeping the sum of required compensation constant always. For each sample, voltage response is achieved and compared with the transient responses reference value as in Example 14. All the samples having their transient responses with in predefined acceptable range are sorted from the total number of samples. Out of these sorted samples, a sample having least compensation cost is selected as optimized participation of reactive power compensation. Therefore, MATLAB codes can be written for getting the solutions of this example as below;

```
% MATLAB code is continued after clubbing all preceding
examples codes together
% variable "loop_ref" shows an array for all reference
parameters
loop_ref=[cost_Qst_ref,cost_Qfc_ref,settlingtime_ref,ma
xvoltage_ref, minvoltage_ref];
 % For producing number of samples satisfying equality
constraints
ql; qig; qsg;
qcom=ql+qig-qsg;
Qst_upper=qcom; Qst_lower=0;
Qfc_upper=qcom; Qfc_lower=0;
Qdemand=qig+ql;  % total  reactive  power  demand  in  the
system
count1=0; sample=1000; % 1000 samples are considered
Qsg=qsg;
Qfc=linspace(Qfc_lower,Qfc_upper,sample);  %  initialize
the reactive power from FC
 % for producing the samples for FC and ST participa-
tion satisfying equality constraints
for n1=1:sample
 x111=Qfc(n1);
 x333=-x111-Qsg+Qdemand;
 if x333<=Qst_upper && x333>=Qst_lower
 count1=count1+1;
 Q_fc(count1)=x111;
 Q_st(count1)=x333;
 end
 end
count1; % it gives number of samples
possible_participation=[Q_st' Q_fc'];  %  the  values  of
each participation between ST and FC
%%%% cost calculation for each sample
cost_Qfc=0.132.*(Q_fc.*(pl_base)./1000);
cost_Qst=(1000.*(Q_st.*pl_base./1000)./(8760.*15)).*((0
.0002466.*Q_st.*Q_st)-(0.2243.*Q_st)+150.527);
cost=cost_Qfc+cost_Qst;
cost_Q=[Q_st' Q_fc' cost_Qfc' cost_Qst' cost'] % matrix
for cost comparison for each sample data
% transient study parameters for all sample data
for n=1:(count1-1)
costofQ(n)=cost(n);
% Fixed Capacitor constant for each sample
xc=vac*vac/(Q_fc(n));
k12=2*vpu/xc;
```

```
% STATCOM constants for each sample
m=p*sqrt(6)/(6*pi);
k=1/m;
vdc=vac/k;
is=(Q_st(n))/(sqrt(3)*vac); % in Ampere
icr=(5/100)*(2*sqrt(2)*is);
lac=(sqrt(2)*vac/(6*a_st*fs*icr)); % in henry
B=1/(w*lac);
alpha=acosd(((k*vdc)^2*B-(Q_st(n)))/(k*vdc*vac*B));
k11=k*vdc*vac*B*sind(alpha);
k12=-(k*vdc*B*cosd(alpha));
% variables for running simulink model of IHES
qsg;
qst=Q_st(n);
qfc=Q_fc(n);
 sim('simforpaperkW');
 n
plot_t=sim_v.time;
plot_v=sim_v.signals.values;
 % To check the voltage response stable condition
z=size(plot_v);
z=z(1,1);
counter=0;
vforlocalmaxima=plot_v;
for zz=2:z-1
 if vforlocalmaxima(zz)>0
 if vforlocalmaxima(zz)>vforlocalmaxima(zz+1) && vfor-
localmaxima(zz)>vforlocalmaxima(zz-1)
 counter=counter+1;
 local_maxima(counter)=vforlocalmaxima(zz);
 end
 end
end
if local_maxima(1)>local_maxima(2)
loop_1=lsiminfo(plot_v,plot_t);
loop_2=stepinfo(plot_v,plot_t);
loop_data11=struct2cell(loop_1);
loop_data1=cell2mat(loop_data11);
loop_data22=struct2cell(loop_2);
loop_data2=cell2mat(loop_data22);
loop_setlingtime_opt(n)=loop_data1(1);
loop_minvoltage_opt(n)=loop_data1(2);
loop_maxvoltage_opt(n)=loop_data1(4);
loop_risetime_opt(n)=loop_data2(1);
loop_overshoot_opt(n)=loop_data2(5);
```

```
loop_undershoot_opt(n)=loop_data2(6);
else
loop_setlingtime_opt(n)=100;
loop_minvoltage_opt(n)=100;
loop_maxvoltage_opt(n)=100;
loop_risetime_opt(n)=100;
loop_overshoot_opt(n)=100;
loop_undershoot_opt(n)=100;
end
end
pi_sample_array=[costofQ'        loop_settlingtime_opt'
loop_maxvoltage_opt' loop_minvoltage_opt']
%%%%% for pi based sample sorting
count3_loop=0;
for count2_loop=1:count1-1
 if
loop_maxvoltage_opt(count2_loop)<=maxvoltage_ref+0.05
&&
abs(loop_minvoltage_opt(count2_loop))<=abs(minvoltage_r
ef)+0.05                                              &&
loop_setlingtime_opt(count2_loop)<=settlingtime_ref+.01
 count3_loop=count3_loop+1;
 loop_Q_st(count3_loop)=Q_st(count2_loop);
 loop_Q_fc(count3_loop)=Q_fc(count2_loop);
 loop_cost_Qfc(count3_loop)=cost_Qfc(count2_loop);
 loop_cost_Qst(count3_loop)=cost_Qst(count2_loop);
 loop_cost(count3_loop)=cost(count2_loop);

loop_MMaxvalue_Vr(count3_loop)=loop_maxvoltage_opt(coun
t2_loop);

loop_MMinvalue_Vr(count3_loop)=loop_minvoltage_opt(coun
t2_loop);

loop_rrisetimevalue(count3_loop)=loop_risetime_opt(coun
t2_loop);

loop_ssettlingtimevalue(count3_loop)=loop_setlingtime_o
pt(count2_loop);
 end
 end
count3_loop;
loop_sample_array1=[loop_cost' loop_ssettlingtimevalue'
loop_MMaxvalue_Vr' loop_MMinvalue_Vr']
 %loop_oovershoot_opt' loop_uundershoot_opt'
```

```
mincost = min(loop_cost);
for z=1:count3_loop
 nit=loop_cost(z);
 if nit==mincost
 break
 end
end
z;
% Hence solution for optimize participations of FC and
ST are
qst=loop_Q_st(z)
qfc=loop_Q_fc(z)
qst_cost=loop_cost_Qst(z)
qfc_cost=loop_cost_Qfc(z)
total_cost=loop_cost(z)
```

Therefore, the results for the above given MATLAB program can be summarized as,

Reactive power from ST = 0.0936 pu MVAR
Reactive power from FC = 0.1570 pu MVAR
Compensation cost from ST = 0.0268 \$ per h
Compensation cost from FC = 0.0052 \$ per h
Total Compensation cost for optimized participation = 0.0320 \$ per h

Example 17 Compare the voltage response for IHES for reference case having ST only and optimized participation of reactive power compensation using FC and ST together. Also compare the settling time, voltage dip and voltage rise, reactive powers from FC and ST and compensation costs in both the cases.

Solution The voltage responses are obtained by expanding the MATLAB codes given in Example 16. The voltage response comparison is given in Fig. 15 and the settling time, voltages dip and voltage rise in both the cases are tabulated in Table 2.

8 Conclusion and Future Scope

This chapter explains the economical benefits of hybrid participations of static and dynamic reactive power compensators in voltage control studies for IHES. It is elaborated how the rating of a STATCOM can be reduced with the use of an FC so that the overall compensation cost may be reduced up to the extent of voltage variation within the permissible range. The use of dynamic compensator (STATCOM) alone gives a technically viable solution, but the introduction of static compensator (FC) can provide a technically and economically viable solution. Results explain how the total compensation cost can be reduced by introducing static compensator along

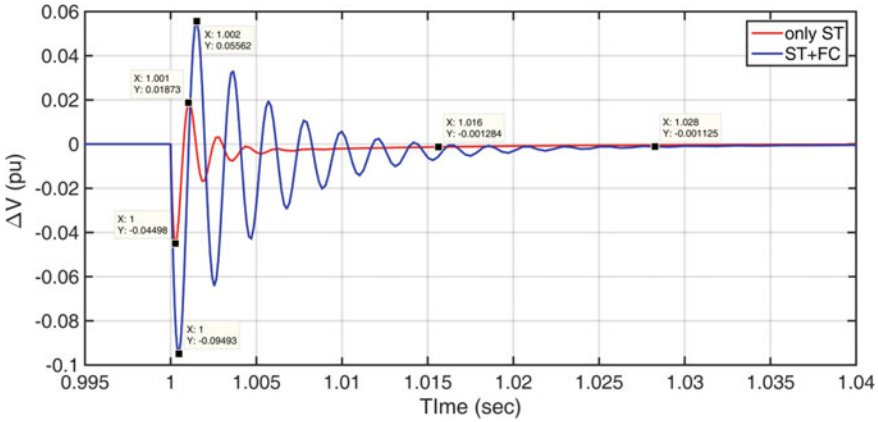

Fig. 15 Voltage response comparison for ST alone and ST & FC together as reactive power compensator

Table 2 Comparative study of transient parameters for voltage response

Response parameters	ST only	ST + FC
Settling time (s)	1.016	1.028
Voltage dip (pu)	−0.04498	−0.09493
Voltage rise (pu)	0.01873	0.05562
Reactive power from FC (pu, MVAR)	0	0.1570
Reactive power from ST (pu, MVAR)	0.2506	0.0936
Compensation cost from FC ($ per hour)	0	0.0052
Compensation cost from ST ($ per hour)	0.0717	0.0268
Total compensation cost ($ per hour)	0.0717	0.0320

with dynamic compensator for generating reactive power for steady state conditions. MATLAB codes are developed for choosing the optimized participations of FC and STATCOM for voltage control studies in IHES. In this chapter, main objective was towards the achievement of optimize participation of reactive power compensation using FC and STATCOM for getting an economical viability of reactive power compensation as ancillary service for the remote area situated consumers. Still, this study has enormous future research scopes in the area of reactive power compensation and voltage control in terms of advance methods to estimate exact parameters of induction generator, modelling of other FACTS device for getting compensation techniques technically and economically, study with online load scheduling, estimation of gain constants of regulator used in FACTS devices by advanced algorithm, introducing to IHES in grid connected system etc.

Key Terms and Their Definitions

Static Compensator: Compensating devices for those reactive power generations can not be changed depending on the time.
Dynamic Compensator: Compensating devices for those reactive power generations can be changed easily as per requirement with time.
Reactive power compensators: To control the system voltage, an additional reactive power is supplied to the system. Such devices are called reactive power compensator.
Compensation cost: Cost asked by the power seller for providing the compensation in system. The actual compensation cost depends on the type of the device used because each device has its own cost function.
Ancillary services: Ancillary services are defined as the additional services provided by the power seller to upgraded the power quality for utility.

MATLAB Code

MATLAB Codes are given within the chapter with examples.

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