A BESS SUPERVISORY CONTROLLER FOR MICROGRID PERFORMANCE ENHANCEMENT

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ABSTRACT
Modeling, simulation and performance evaluation of an electrical microgrid with battery energy storage system are carried out in this article. A detailed dynamic model of a non-autonomous microgrid which has generation from photovoltaic, fuel cell, wind generation system and conventional inertial sources, along with their power electronic circuits and associated filters is developed. The simulations are performed to evaluate transient stability of the microgrid under various contingencies. A decoupled central battery energy storage controller is proposed as a supervisory control to improve system stability. The controller parameters were designed using biogeography based optimization (BBO) procedure. Simulation studies show that the BESS supervisory control is able to restore normal system operation to the otherwise unstable conditions.

KEY WORDS
Battery energy storage; biogeography based optimization; distributed generation; microgrid; P-Q decoupled control

1. Introduction
In recent years, the structure of electrical power systems has changed significantly. Owing to the exponential increase in energy consumption and rapid decline in fossil fuels, research on renewable energy sources and the interest in their local connection at the distribution level has increased [1]. The increased use of renewables has led to technological developments in the distributed generation (DG) units. Various renewable sources such as photovoltaic (PV), fuel cells (FC) and wind power (WG) participate in electrical power generation to replace conventional system from the base load [2]. Interconnection of renewables through VSI (voltage source inverters) introduce many technical challenges which require extensive research to provide unhindered operation, control and protection of new systems[3]. Due to uncertain nature of power obtainable from renewables, the inertial absence, generation of switching harmonics, wide-band of transients and limited overload capability are few of the problems that arise with inverter interfaced DGs [4]. The overall power management and sharing of power among different sources is also a major challenge for a distribution system [5].

The concept of microgrid has evolved due to exhaustive penetration of power from renewable DG sources and their presence at distribution level. A microgrid has two operating modes, the non-autonomous mode and islanded mode. The DG units employed in a microgrid can be inertial machines such as micro turbines that can be connected directly to utility grid or non-inertial type requiring the use of power electronic circuitry for interface with the grid. In the non-autonomous mode, the DG units are controlled to feed certain power into the network at an established voltage, thus behaving as a controllable source or load as determined through generation, load mix and market policies [6]. In the islanded mode, the microgrid will provide adequate power to local sensitive loads and maintain services within the microgrid [7].

Increase in the penetration of DG units in distribution networks, can have operational problems under faulted conditions and instability under small disturbances such as generation change or load change [8]. Hence it is important for a microgrid to recover itself from perturbations and thus maintain its stability in both the operating modes. In the last few years, several stability problems associated with the DG units in distribution networks have been reported in literature [9]. These problems have been mainly attributed to the control failures of individual inverters.

In the traditional power systems when some disturbance occurs, the system frequency changes due to the kinetics of the rotating parts. Since the majority of renewable sources in a microgrid do not contain inertial parts there is no such frequency response phenomenon. The interfacing inverter of a micro source can be controlled to mimic the operation of a synchronous generator and appropriate power sharing mechanism can be designed [10].

The stability problems associated with the large participation of renewable power sources having rapid power variations can be overcome by employing energy storage devices in combination with a voltage source converter to act as a central controller to the microgrid. The storage device can act as a dispatchable DG source and swiftly exchange power with utility grid [11]. Several fast response and bulk energy storage technologies viz. batteries, super capacitors, flywheels, superconducting
magnetic energy storage (SMES) systems can be employed [12], [13]. The central controller to a microgrid can monitor the active and reactive power flows from various DGs in order to balance the total generation and load at the microgrid. Compensation of real and reactive power in the distribution system will be performed by the central storage controller thereby enhancing the transient stability boundaries [13].

This article presents a detailed dynamic model of a grid-connected microgrid system containing fuel cell, PV generator and wind system in addition to a conventional micro-turbine. Battery storage along with VSC (voltage source converter) has been used to control the above microgrid. Effectiveness of the controller in mitigating the abnormal conditions is assessed by simulating disturbance conditions on the microgrid.

2. The Microgrid System Model

The microgrid configuration shown in Figure 1 consists of a small scale micro-turbine along with synchronous generator, photovoltaic system, fuel cell system and a PMSG wind system. A battery storage device is modeled as a central managerial controller to coordinate power flow among various units.

Figure 1. Microgrid system configuration

The mathematical description of each of the component in the microgrid is presented below.

2.1 The Micro-Generator

The conventional generation system is modeled as a synchronous alternator driven by a gas-turbine or a diesel engine generating electrical power of fundamental frequency which makes possible for direct connection to the grid. A third order model consisting of the swing equation and internal voltage equation of an alternator is being used as a dynamic model for synchronous generator [14].

\[
2H \frac{d^2 \delta}{d t^2} = P_m - P_e - D(\omega - \omega_b)
\]

Here \( H, \delta, \omega_b, P_m, P_e, \omega \) stand for inertia constant, rotor angle, base angular frequency, power input, power output, and generator frequency, respectively. The internal voltage \( e_q \) is given by the following equation,

\[
\frac{d e_q}{d t} = \frac{1}{T_d} [E_{fd} - e_q - (X_d - X_q)I_{fd}]
\]

2.2 The Fuel Cell

Fuel cells being a source of renewable energy are electrochemical devices that convert chemical energy obtained from an electrolytic reaction directly to electrical energy. These devices require the use of power converters to drive the interfaced load or feed power to the grid. A proton exchange membrane fuel cell stack (PEM-FC) is modeled through a simplified generic electrical circuit where in the fuel cell is considered as a controllable voltage source in series with a constant resistance [15]. Characteristics of which can be expressed through relation,

\[
E = E_{oc} - NA \ln \left( \frac{i}{I_0} \right) \frac{1}{s^{\frac{kT}{3} + 1}}
\]
Here, the open circuit voltage is \( E \), \( N \) denotes the number of series connected cells, \( A \) is the Tafel slope, \( i_0 \) is the exchange current, \( R_{ohm} \), the internal resistance, \( T_d \) the response time (at 95% of the final value) and the fuel cell stack current and voltage denoted by \( i_{fc} \) and \( v_{fc} \) respectively.

The transient relation governing the DC-boost converter can be derived through KVL as,

\[
\frac{di_{fc}}{dt} = \frac{1}{L_{dcb}} [v_{fc} - (1 - dr_{fc})v_{defc}]
\]

\( L_{dcb} \) represents the inductance of DC-boost converter, \( dr_{fc} \) refers the duty ratio and \( V_{defc} \) is the dc-link capacitor voltage.

The voltage across the dc-link capacitor has a dynamic relation given by,

\[
\frac{dv_{defc}}{dt} = \frac{1}{C_{defc}} [i_{dcin} - i_{dcout}]
\]

Considering the currents through inductor and voltages across various capacitors along d-q reference as additional state variables, the complete non-linear model of fuel cell system can be derived. The state variables chosen are as follows,

\[
X_{FC} = [i_{fc}, v_{defc}, i_{fd}, i_{fq}, i_{fd}, i_{fq}, v_{fd}, v_{cfq}]
\]

### 2.3 The Photovoltaic System

The connection arrangement of a PV module with the utility grid is shown in Figure 4, which depicts the use of extensive power electronic circuitry and filtering components.

The PV cell has been modeled through a general approximate electrical equivalent circuit. Due to low power output of a cell, several series and parallel arrangement of solar cells will constitute a PV module, producing power of considerable value. Figure 5 shows the representation of a PV cell.

The characteristic relation pertaining to the PV circuit model is,

\[
i_{pp} = i_{sc} - i_{sc} \left[ e^{\left(\frac{v_{pp} + i_{pp}R_s}{n_{PV}}\right)} - 1 \right]
\]

The other dynamical relations can be written by considering the currents through various inductors and the voltage across various capacitors as state quantities.

For the DC-boost converter employed in the power conditioning unit of PV system the dynamical relation can be expressed as,

\[
\frac{dv_{pv}}{dt} = \frac{1}{L_{dcb}} [v_{pv} - (1 - dr_{pv})v_{depv}]
\]

Referring to the Figure 4, the dc-link capacitor has a dynamic voltage across it as given by,

\[
\frac{dv_{depv}}{dt} = \frac{1}{C_{depv}} [i_{dcin} - i_{dcout}]
\]

The currents in d-q reference frame, through the filter, before and after the filtering operation can be considered as additional state variables giving following [16],

\[
[i_{pf}, i_{pf}, i_{pf}, i_{pf}]
\]

Two more differential equations arise when dynamics of the filter capacitor are taken into account as,

\[
\frac{dv_{cpd}}{dt} = \frac{1}{C_{pf}} \left( i_{pf} - i_{pd} \right) + \omega_0 \omega V_{cpd}
\]

\[
\frac{dv_{cpq}}{dt} = \frac{1}{C_{pf}} \left( i_{pf} - i_{pq} \right) - \omega_0 \omega V_{cpd}
\]

Thus state space model for the PV system when connected to grid includes the following state vector,

\[
X_{PV} = [i_{pv}, v_{depv}, i_{pf}, i_{pf}, i_{pf}, i_{pf}, v_{cpd}, v_{cpd}]
\]

### 2.4 The Wind Energy System

Figure 6 shows a horizontal axis wind turbine driving the rotor of a permanent magnet synchronous generator through a gearless drive train. Field excitation to the generator is obtained through permanent magnets mounted on the generator rotor. Power electronic converters connected between the stator of PMSG and the grid provides an AC voltage of constant grid frequency to be able to feed the grid. The equations of the wind turbine, the gearless drive train, the PMSG, the converter circuits and transmission line connected at grid side give the model of the wind generation system [17].

The mathematical representation a wind turbine driving a permanent magnet synchronous generator (PMSG) along with the associated power electronic converter circuits is explained, and non-linear state space models are derived.
Considering the wind turbine and PMSG set as a two-mass drive train, the electromechanical equations in terms of the turbine rotor speed $\omega_t$, the torsional angle $\theta_s$, the PMSG rotor speed $\omega_w$ and its rotor angle $\delta_w$ are,

$$\frac{d\theta_s}{dt} = \omega_g(\omega_t - \omega_w)$$  \hspace{1cm} (17)

$$\frac{d\omega_t}{dt} = \frac{1}{2H_t} (P_{sw} - K\theta_s - D_t(\omega_t - 1))$$  \hspace{1cm} (18)

$$\frac{d\delta_w}{dt} = \omega_g(\omega_w - 1)$$  \hspace{1cm} (19)

$$\frac{d\omega_w}{dt} = \frac{1}{2H_g} (K\theta_s - P_{ew} - D_g(\omega_w - 1))$$  \hspace{1cm} (20)

The transient relations of the stator current output of PMSG taken along d-q reference frame will give the dynamics of the wind generator as given below,

$$\frac{dI_{gwd}}{dt} = \frac{\omega_g}{x_{qw}} \left[-R_{gwd} I_{gwd} + \omega_w X_{qw} I_{gwd} V_{gwd}\right]$$  \hspace{1cm} (21)

$$\frac{dI_{gwq}}{dt} = \frac{\omega_g}{x_{qw}} \left[-R_{gwq} I_{gwq} - \omega_w X_{dw} I_{gwq} + \omega E_{fdw}\right]$$  \hspace{1cm} (22)

The relation governing the electromechanical torque produced by the PMSG is,

$$T_{ew} = E_{fdw} * I_{gwd} + (X_{qw} - X_{dw}) I_{gwd} I_{gwq}$$  \hspace{1cm} (23)

Similar to the filter circuit shown in Figure 4 the additional variables will be included in the state space model. Thus the complete non-linear representation of wind system is given by the following state vector.

$$X_{wind} = \left[\theta_s, \omega_t, \delta_w, \omega_w, I_{gwd}, I_{gwq}, V_{dcw}, I_{wfd}, I_{wfq}\right]$$  \hspace{1cm} (24)

State variables from the converter and filter circuits are,

$$X_{wind} = \left[I_{wfd}, I_{wfq}, V_{ewd}, V_{ewq}\right]$$  \hspace{1cm} (25)

### 2.5 The BESS Storage Controller

A central energy storage device is introduced to facilitate efficient power sharing among the various DGs and also takes corrective action when necessary [18].

The battery energy storage system considered in this study is shown in Figure 7. It consists of a battery coupled to the PCC bus through a voltage source converter. The converter can be controlled in order to facilitate the power flow to and from the storage battery.

Under steady state operating region, the power electronic converter connecting energy storage system with the microgrid floats and no power flow takes place from the battery. An ideal DC voltage source $V_{batt}$ along with a series resistance $R_b$ accounting for electrical losses describes the behavior of battery. Modulation index $m$ of the VSC has the role for compensating the reactive power required while the storage device provides the necessary real power supplement during transients through control of $\Psi$ [19].

Inclusion of the converter transformer the voltage-current dynamical relation for the VSC can be written as,

$$L_{st} \frac{dI_{st}}{dt} + R_{st} I_{st} = V_{st} - V_s$$  \hspace{1cm} (26)

A controllable voltage source model has been utilized for the VSC with voltage relation as,

$$V_{st} = m V_{dcs} \Psi$$  \hspace{1cm} (27)

Decomposition of the VSC current into d-q frame and taking into per unit system will result,

$$\frac{dI_{dcs}}{dt} = \left[ \begin{array}{c} \omega_{gRst} \\ \omega_{gBst} \end{array} \right] \frac{L_{st}}{\omega} I_{dst} + \left[ \begin{array}{c} \omega_{gRst} \\ \omega_{gBst} \end{array} \right] \frac{L_{st}}{\omega} I_{qst} + \frac{m V_{dcs} \cos(\psi + \theta) - V_{st}}{L_{st}} + \frac{m V_{dcs} \sin(\psi + \theta) - V_{qst}}{L_{st}}$$

Assuming the voltage source converter to be lossless, by the application of KCL at the DC side of VSC will yield the dynamics of DC-link capacitor,

$$\frac{dV_{dcs}}{dt} = -\frac{m}{C_{dcs}} \left( I_{dst} \cos(\psi + \theta) + I_{qst} \sin(\psi + \theta) \right)$$  \hspace{1cm} (28)
By making a transformation on the VSC currents, the above equations could be rewritten to produce a decoupled P-Q control strategy. The block diagram for the decoupled controller is shown in Figure 8.

![Decoupled P-Q control strategy](image)

Figure 8. Decoupled P-Q control strategy for the storage system

The composite model of the microgrid along with the incorporation of the central BESS controller will yield a non-linear dynamic model being represented as,

$$\frac{dx}{dt} = f(x, u)$$

(29)

The control vector is obtained as,

$$u = \left[ m_p, \psi_p, m_f, \psi_f, m_c, \psi_v, \psi_v, m, \psi \right]$$

(30)

2.5.1 Optimization of Controller Parameters

The decoupled controller requires the reference values of real and reactive power in order to achieve the central control operation. In this work, the microgrid voltage magnitude and phase angle are used to generate the reference real and reactive powers. As depicted in Figure 8, the P-Q decoupled controller has 8 PI gains obtained due to 4 control circuits which are required to be optimized.

We propose the application of iterative search procedure, guided through a fitness function, to carry out the parameter search. Bio-geography based optimization (BBO) is applied to tune the parameters of the central controller.

The following non-linear objective function is proposed to be employed as performance criteria,

$$J = \min \int_{t=0}^{t=tsim} t[a_1|\delta o| + a_2|\delta V_s| + a_3|\delta V_{des}|]$$

(31)

The fitness function $J$ is the sum of the deviations in the rotor speed of micro-generator $\delta o$, the microgrid voltage $\delta V_s$ and the DC-link voltage of the VSC $\delta V_{des}$ employed in the central controller.

BBO is inhabitants based stochastic operated evolutionary search algorithm for global optimization which simulates the biogeography of nearby habitats and how they interact with each other. It is described by its efficiency, fewer parameters and ability to work with any type of fitness function. This technique was introduced by Dan Simon [20]. Individuals representing habitat or islands evolve over several generations stochastically and guided through fitness called habitat suitability index (HSI), to reach an optimal solution. Each habitat is represented by D dimensions depicting the number of control variables. Exchange of features among various habitats takes place through migration (emigration & immigration) of different species. Similar to other evolutionary algorithms, the BBO technique begins with initializing the inhabitants randomly within the search space and carrying out elitism, migration and mutation processes iteratively until the termination criteria are met.

The various steps involved in the search process are illustrated below.

A. Initialization

In this step, it is required to specify the number of suitability index variables D with their corresponding constraints and other BBO parameters such as maximum species count, the maximum migration rates and elitism setting. The initial population is generated randomly within the search space for each control variable based on the relation,

$$x_{k,i}^N = x_{i,min}^N + \text{random}(x_{i,max}^N - x_{i,min}^N)$$

(32)

B. Migration

After evaluating the initial habitats for fitness, two processes named immigration (import of species from nearby habitats) and emigration (export of species to other nearby habitats) are performed probabilistically on the species to yield better solutions.

C. Mutation

Mutation of each of the habitat is then carried out based on the probability relation given below.

$$\frac{dP_i}{dt} = -(\lambda_3 + \mu_3)P_i + \mu_{s+1}P_{s+1} + \lambda_{s-1}P_{s-1}$$

(33)

D. Elitism

In each iteration, a pre specified numbers of habitats are copied into the next generation.

3. Simulation Studies

The microgrid system with the DG’s, microalternator and BESS supervisory controller, shown in Figure 1, was simulated to investigate the controller performance. At steady state, the generations from the different DG’s are, the micro generator 0.2 pu, PV array 0.8 pu, fuel cell stack 0.8 pu, wind system 0.8 pu, connected load is real power 0.8 pu, reactive power 0.15 pu, the remaining power is delivered to the grid. A 15% input torque pulse for 300ms on the micro generator was considered for evaluation of the controller. The operating point is selected so as to give rise to an unstable condition in the absence of any control. The optimal controller parameters of Figure 8, obtained through the BBO search algorithm are given in Table 1.
The system responses following the disturbance are shown in Figure 9-15. The variation of the microgrid bus voltage following the disturbance is displayed in Figure 9. Figure 10 shows the deviations in microalternator load angle.

![Figure 9. Microgrid voltage variation following a 15% torque pulse for 300 ms on micro-alternator, with and without BESS central control](image1.png)

![Figure 10. Microgenerator load angle variation with and without BESS central control](image2.png)

It can be observed from the two figures that in the absence of control action following the disturbance the transients increase gradually initiating tripping of the micro generator unit. On the contrary, with the application of BESS central controller the microgrid voltage stabilizes in a short while after the disappearance of the contingency. The reactive power support needed to re-establish the voltage is provided by the storage system converter while the necessary real power required during the transient is obtained from the battery unit.

![Figure 11. PV array current output variation with and without BESS central control](image3.png)

![Figure 12. Fuel-cell stack current variation with and without BESS central control](image4.png)

![Figure 13. PMSG stator current variation with and without BESS central control](image5.png)

The output current variations for the PV unit, fuel cell stack and wind generator are displayed in Figure 11-13.

With the supervisory BESS controller the transient stability boundaries are enhanced following the disturbance. The variations in the central controller DC-
link voltage and the real and reactive power injections into the microgrid are shown in Figure 14 and Figure 15 respectively.

From Figure 15 it can be noted that following the pulse in mechanical torque, the net real power in the system increases which is compensated by the central BESS controller. Microgrid voltage is maintained through reactive power exchange of the converter.

4. Conclusion

Dynamic performance of an electrical microgrid with micro-alternator and renewable like photovoltaic, fuel cell and wind generator is investigated. Inclusion of a battery energy storage as a central controller is explored. The control strategy for the energy storage device has been designed through P-Q decoupled central controller to monitor the power flow scenarios and compensate for real and reactive power imbalance under contingencies. Optimization is achieved through a bio-geography based optimization method which is superior in terms of efficiency, robustness and convergence criterion.

The proposed BESS decoupled central control strategy is seen to re-establish the microgrid voltage with the real and reactive power injected during transients. The real power support from the BESS helps to damp the oscillations quickly.

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References


