Intelligent Voltage and Reactive Power Management in a Stand-alone PV based Microgrid

Asit Mohantya\textsuperscript{a}, Meera Viswavandy\textsuperscript{a}, Dillip Mishra\textsuperscript{a}, Pragyan Paramita\textsuperscript{b}, Sthita P Mohantya\textsuperscript{a}

\textsuperscript{a}CET Bhubaneswar, India
\textsuperscript{b}VSSUT Burla, India.

Abstract

This paper focuses on application of intelligent methods behind TCSC controller for Reactive Power compensation in an isolated hybrid system and enhancement of the stability of the system. A small signal linear model of the hybrid PV based microgrid model is considered and simulated for different solar insolations, Wind inputs and with uncertain loading conditions. The reactive power control as well as the stability analysis have been carried out with TCSC Controller. A feed forward neural network with back propagation technique has been designed for tuning the parameters of TCSC controller. Simulation result verify the fact that the system parameters improve by the application of ANN and attend steady state value with lesser time and complexities.

Keywords: PV-Wind-Diesel Microgrid; IG; TCSC; ANN Controller.

1. Introduction

Power systems efficiency is always improved by the management of reactive power. Reactive power supports the voltage, which should be controlled for enhancing system reliability. Also reactive power has an effect on the security of the power system as it affects the voltage profile of the whole system. Voltage control is very important for the electrical power system as far as proper operation of electrical power equipments like generators, motors are concerned. Control of reactive power and voltage stability help the power system in reducing transmission losses and prevent voltage collapse. The voltage profile of power system is controlled by the management of production and absorption of reactive power.

\* Corresponding author. Tel.: 919437920530
E-mail address: asithimansu@gmail.com
Capacitor banks are frequently implemented to compensate reactive power in the power system. But in case of power system based on renewable energy sources like wind, solar etc. which are quite unpredictable, fixed capacitors cannot meet the challenge to compensate reactive power. [1]-[2]. These challenges like voltage instability and reactive power compensation are better managed by the use of FACTS (Flexible AC Transmission System) devices [3]-[7]. Now a days Standalone hybrid power systems are set up in large scale at remote places to cater the local power demands. These particular places are located away from the main grid and getting power from the grid becomes a daunting task for them. Renewable energy sources like Wind, PV, Fuel cell etc. with Diesel back up are commonly used as hybrid system. Synchronous generators are used in case of Diesel Generator and SCIG/DFIG/PMIG are preferred in Wind Turbine for their rugged characteristics [1]-[3]. In this paper a wind–diesel-pv hybrid system consisting of both synchronous generator and Induction generator is discussed. The Induction generator requires reactive power which is provided by the SG based Diesel engine. The reactive power capability of SG is limited and therefore additional compensating devices are required to face the problems like voltage fluctuation and instability

FACTS devices like SVC, STACOM and other are utilised to compensate the reactive power of the power system which are extensively used for voltage and angle stability studies in hybrid power system. Control of reactive power is an important aspect of hybrid power system and during absence of reactive power the system goes through wide voltage variations and lots of fluctuations. This work proposes an ANN based TCSC Controller[4-7] for reactive power management and stability enhancement in a standalone wind diesel PV hybrid system. The proposed controller tunes the gains of the PI Controller and enhances the transient stability and reactive power compensating capability of the system. By the application of ANN controller in power system many problems are easily solved,[8]-[15]. ANN works similar to the working of biological nervous systems. It consists of a large number of interconnected processing elements (neurons) working together to solve a problem and is designed for a specific application through learning process which adapts the synaptic connections of the neurons. The main merits of ANN are the relationship between the input and output data s for an unknown relationship or complex function.

The gains of the PI controller depends totally upon the type of reactive power load for optimum performance. Due to the variable nature of the load, the PI gains setting of TCSC are adjusted after proper tuning. The paper focuses the ANN based approach to tune the PI gains of the TCSC controller over a wide range of load characteristics. For the simulation the multi-layer feed-forward ANN tool box of MATLAB with the error back-propagation training method is used. This paper discusses a small signal model of wind-diesel system for analysis of transient stability and reactive power compensation with introduction of ANN based TCSC controller for 5% load change. Section II describes the whole system and the detailed mathematical model of it. Detailed work with application of of ANN controller for tuning the gains of PI controller is discussed in section III. Finally the simulation results with detailed descriptions are represented in section IV and conclusion part in Section V.

2. System Configuration and its Mathematical Modelling

The isolated microgrid basically consists of Induction generator (IG) based wind turbine, Synchronous generator (SG) based diesel engine as backup with IEEE exciter 1 connected to electrical loads. The block diagram
of the same is shown in Fig. 1. The active power is provided by the Induction generator and Synchronous generator. Reactive power need of the Induction generator and Load is compensated by TCSC and is improved with ANN based TCSC controller. TCSCs are considered better reactive power compensating devices in comparison to other FACTS devices like SVC and STATCOM.

Fig. 1 Wind-diesel-PV hybrid Power system with TCSC

Fig. 2. Small signal transfer function model of Wind-diesel-PV hybrid system with TCSC
The balanced reactive power equation of (SG, TCSC, IG and LOAD) is expressed as
\[ \Delta Q_{PV} + \Delta Q_{SG} + \Delta Q_{COM} + \Delta Q_{L} + \Delta Q_{IG} = \Delta Q_{PV} \]

Due to small change in reactive power load \( \Delta Q_L \), the system terminal voltage varies which affects the reactive power requirement of other members of the system. The final reactive balance equation is equal to
\[ \Delta Q_{PV} + \Delta Q_{SG} - \Delta Q_{L} - \Delta Q_{IG} = 0 \]

and the value changes the system output voltage. The System Model Equation is governed by the transfer function equation which is given below
\[
\frac{\Delta Q_{PV}}{\Delta e} + \frac{\Delta Q_{SG}}{\Delta e} + \frac{\Delta Q_{COM}}{\Delta e} + \frac{\Delta Q_{L}}{\Delta e} + \frac{\Delta Q_{IG}}{\Delta e} = \frac{d}{dt} (\Delta E_m) + D\Delta V
\]

The equivalent circuit of the Induction machine has been considered for the state space modelling of Induction generator. The real and reactive power delivered by the induction generator are given by
\[
R^2 + \frac{X_m}{X_m} V^2 = \frac{V}{X_m} (R + X_m Q)
\]

As the term \( \frac{V^2}{X_m} \) contributes towards electromagnetic energy storage equation for the modelling, the reactive power absorbed by the Induction Generator is given by
\[
Q_{IG} = \left( \begin{array}{c} \frac{V}{X_m} \\
\frac{X_m}{X_m} \end{array} \right)^2
\]

The Small signal model of the hybrid system has been depicted in Fig. 2. Fig. 3 shows the photovoltaic model based upon voltage source converter (VSC) with dq current control. Here in this model two architectures based on PQ and PV have been used for stability studies. The small signal transfer function models with steady-state gain and closed-loop control transfer functions are used as because both the models provide similar output and same type of results. The hybrid system PV is considered as a potential source which plays a great role in reactive power exchange between the system elements. The PV Converter provides reactive powers when it is connected to the bus bar
\[
Q = \frac{VE_m}{X_m} - \frac{V}{X_m} (V_{cos(\delta)} - V)
\]

For the Diesel engine system, the modified synchronous generator equation is
\[
Q_{SG} = \frac{(E_{q}V_{cos(\delta)} - V^2)}{X_d}
\]

(Transient condition) and for incremental change,
\[
\Delta Q_{SG} = \frac{V_{cos(\delta)}}{X_d \Delta E_q} + \frac{E_{q}V_{cos(\delta)} - 2V}{X_d \Delta V}
\]

\[
\Delta Q_{SG}(s) = K_a \Delta E_q(s) + K_b \Delta V(s) \text{ Where } K_a = \frac{V_{cos(\delta)}}{X_d} \text{ and } K_b = \frac{(E_{q}V_{cos(\delta)} - 2V)}{X_d}
\]
Thyristor Controlled Series Capacitor (TCSC) is one of the series FACTS devices and are utilised to control power flow in transmission lines and helps in improving stability and reactive power compensation. TCSC is used to improve power system stability by adjusting the reactance of transmission line. TCSC needs some more supplementary input signals than other FACTS devices. Several controllers are used to perform this control strategy such as conventional PI controller, rule based controller and energy function based controller. Here in this work a back propagation algorithm based ANN Controller is used for TCSC to control the reactive power. TCSC based controllers are based on conventional lead-lag structure. The input signal to the controller is speed deviation of the generator. The controller block consists of a gain block, washout block and two stage lead-lag blocks. In the controller wash out block act as high pass filter. The phase compensation acts to provide the necessary phase – lead characteristics to compensate for any phase lag between the input and the output signals. The small signal model of TCSC as in Fig. 4 is taken for simulation.

\[
X_{TCSC}(\alpha) = \frac{X_C X_L(\alpha)}{X_L(\alpha) - X_C} \tag{7}
\]

\[
X_L(\alpha) = X_L \frac{\pi}{\pi - 2\alpha \sin \alpha} \tag{8}
\]

\(\alpha\) is the delay angle measured from the crest of capacitor voltage.

\[ U_{TCSC} \rightarrow K_T \left( 1 + \frac{1}{T_T} \right) \rightarrow X_{TCSC} \]

\[ \Delta \omega \rightarrow K_{TS} \]

\[ \frac{1 + sT_{T_3}}{1 + sT_{T_4}} \rightarrow \frac{1 + sT_{T_1}}{1 + sT_{T_2}} \rightarrow \frac{sT_{TW}}{1 + sT_{TW}} \]

3. Artificial Neural Network

ANN is based upon the neural structure of the brain and It tries to imitate the functioning of the brain, we know that brain stores information and ANN provides a new field of computing that involves the creation of massive parallel networks to solve specific problems. Neurons always provide the ability to remember and apply the previous experiences and ANN works on a same pattern to achieve high computational rates due to massive parallelism fault tolerance capability. The controller uses back propagation algorithm for the training process. In the training process
a set of input output pattern for neural network is required. The ANN network is shown in Fig. 5.

3.1 Back Propagation Algorithm

This algorithm works in the following steps:
Initialization--All the weights threshold levels of the network are randomly distributed in a small range.
Activation--Here the actual outputs of the neuron in the hidden layers are calculated.

\[
y_j(p) = \text{sigmoid} \left( \sum_{i=1}^{n} x_i(p) \cdot w_{ij}(p) - \theta_i \right)
\]

Where \( n \) is the number of inputs of the neurons \( j \) in the hidden layer. So the actual outputs of the neuron in the outer layer

\[
y_k(p) = \text{sigmoid} \left( \sum_{i=1}^{m} x_{jk}(p) \cdot w_{ik}(p) - \theta_k \right)
\]

Training of weights--The error gradient for the neurons in the output layer is calculated.

\[
\delta_k(p) = y_k(p) \left(1-y_k(p)\right) \cdot e_k(p), \quad e_k(p) = y_{dk}(p) - y_k(p)
\]

And the weight corrections are

\[
\Delta w_{jk}(p) = \alpha \cdot y_j(p) \delta_k(p), \quad \text{then the weights at the output neurons are updated as}
\]

\[
\Delta w_{jk}(p+1) = w_{jk}(p) + \Delta w_{jk}(p)
\]

The error gradient of the hidden layer neurons can be calculated

\[
\delta_j(p) = y_j(p) \left(1-y_j(p)\right) \sum_{k=1}^{l} \delta_k(p) w_{jk}(p)
\]

and the weight corrections are

\[
\Delta w_{jk}(p) = \alpha x_j(p) \delta_j(p), \quad \text{when updated the weights at the hidden neuron}
\]

\[
w_{jk}(p+1) = w_{jk}(p) + \Delta w_{jk}(p)
\]

Iteration--An increase of iteration \( p \) by one step and the process should be repeated until the selected error Criterion is satisfied.

3.2 Training of parameters by ANN

The reactive power load voltage characteristics (\( n_q \)) is used as input of the ANN and the outputs are the proportional and integral gains \( k_p \) and \( k_i \) of TCSC controller. The ANN utilises the normalised values of \( n_q \) as input and produces output in normalised way and is converted to actual one. The process of determination of weights is known as training of the learning process and an input output pairing is first prepared prior to the conducting of training process. Based on the loading conditions the set is first developed by calculating the desired PI controller gains. The typical range lies between 0.0 to 4.0, taking the exponent of load voltage characteristics is prepared to cover all typical loads of the power system. The network is trained repeatedly till an optimum agreement between predicted gains and actual gains is achieved. The network is again tested to predict the actual gain settings of the load model. The performance index \( \eta \) is based on integral square error (ISE) and is equal to \( K_i^{\text{min}} \leq K_i \leq K_i^{\text{max}} \) and by minimising the performance index optimised values of \( k_p \) and \( k_i \) are determined. \( \Delta V \) is the voltage deviation, subject to the constraints, \( K_p^{\text{min}} \leq K_p \leq K_p^{\text{max}} \) and \( K_i^{\text{min}} \leq K_i \leq K_i^{\text{max}} \). Table 1 shows the optimum gain settings of TCSC for different reactive –load voltage characteristics.
### Table 1 Optimum gain settings of TCSC

| \( n \) | \( k_p \) | \( k_q \) |
|-----|------|------|
| 0.5 | 30   | 4900 |
| 1   | 35   | 5000 |
| 1.5 | 40   | 5405 |
| 2   | 45   | 5600 |
| 2.5 | 48   | 5707 |
| 3   | 52   | 6008 |
| 3.5 | 54   | 6234 |
| 4   | 56   | 6458 |

### 4. Simulation Results

Simulation has been carried out taking an ANN based TCSC Controller for the wind diesel PV hybrid power system and the settling points and peak overshoots of different parameters of the hybrid system are noted. The input solar insolation is fed as input to the hybrid system. The ANN controller has been used for compensating reactive power and voltage stability of the hybrid power system with a step load change of 5%. The variation of all the system parameters such as small change in reactive power of Synchronous generator, Induction generator, Reactive Power Change of TCSC, Variation in firing angle, Variation in terminal voltage, Variation in field excitation, Variation in armature voltage, and change of armature voltage under transient, etc., as shown in Fig. 6(a) to Fig. 6(d) are studied for the above mentioned disturbance using traditional PI Controller and the ANN controller.

![Fig. 6(a-d) Output of Wind Diesel PV hybrid system using TCSC for 5% load change during transient condition (comparison with ANN Controller)](image)

Fig. 7(a) Maximum deviations  
Fig. 7(b) Settling time with 5% load change

The settling time and peak overshoot in the case of ANN controller is observed to be less in comparison to traditional PI Controller. Simulation results show that the output of ANN Controller is better than the traditional PI Controller. Fig 7 (a) and Fig. 7(b) show the results. Table 2 shows the deviations in parameters.
5. Conclusion

This paper gives a novel solution for the transient stability analysis and reactive power compensation in the wind-diesel-PV hybrid system with the incorporation of ANN based TCSC controller. Results show the Variation of the system parameters with variation of load and it is found that the reactive Power compensation of the model has been achieved. The compensation in case of back propagation based ANN controlled system is better than the conventional system. The proposed ANN controller based hybrid system shows better results in settling time and overshoot. The ANN Controller shows effective improvement and changes in the output by tuning the values of KP and Ki than the conventional PI controller and thereby helps in improving the stability of the system.

Table 2: Comparison between two controllers for 5% load change

|                      | PI Controller | ANN Controller |
|----------------------|---------------|----------------|
| Maximum Deviation    | Settling Time | Maximum Deviation | Settling Time |
| Del V               | 0.0522        | 0.51            | 0.0483        | 0.475 |
| Del QSG             | 0.5252        | 0.50            | 0.5151        | 0.481 |
| Del QIG             | 0.0052        | 0.42            | 0.0051        | 0.401 |
| Del E_c             | 0.0154        | 0.61            | 0.0092        | 0.601 |
| Del Alpha           | 4.1522        | 0.55            | 3.4521        | 0.520 |
| Del Efd             | 0.0492        | 0.64            | 0.0482        | 0.600 |

Appendix : Parameters of PV based microgrid

| System Parameter     | microgrid |
|----------------------|-----------|
| Wind Capacity (Kilowatt) | 150       |
| Diesel Capacity      | 150       |
| PV Capacity          | 150       |
| Load Capacity        | 400       |
| Base Power in KVA    | 400       |

| SYNCHRONOUS GENERATOR | INDUCTION GENERATOR |
|-----------------------|----------------------|
| P_{G0}, KW            | 0.4                  |
| Q_{G0}, kVAR          | 0.2                  |
| E_{0}, pu             | 1.113                |
| E_{0}, pu             | 0.96                 |
| V(pu)                 | 1.0                  |
| X_{0}, pu             | 1.0                  |
| T_{a}, \psi           | 5                    |
| LOAD                  |                       |
| P_{0}, pu in KW       | 1.0                  |
| Q_{0}, pu in KVAR     | 0.75                 |
| \alpha in Radian      | 2.44                 |

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