Reactive Power Control for Regulation of Voltage with Integrated Wind Farms

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***Abstract*— Maintaining the transmission network voltage within a narrow range is required as a performance standard and also to ensure the stability of a power system. Voltage regulation is generally achieved through reactive power control. Controlling reactive power with the aid of Flexible Alternating Current Transmission (FACT) devices is a recent advent to power system operations with many a research ongoing. Further, due to the high penetration of grid connected renewable energy sources, it is becoming a trend to use the inverters associated with the renewable power generators to support voltage regulation. The operation of voltage regulating devices should comply with the variations in consumer demand as well as with the variation in power generation which is increasing becoming more stochastic due to the introduction of more and more intermittent renewable energy resources. This paper discusses a design of a reactive power control algorithm which utilizes conventional as well as inverter based reactive power support. The performance of the control algorithm when embedded in a power system simulation environment validates its ability to maintain specific voltage levels in the power system. The Sri Lankan power system is taken as the study case for all presentations in this paper.**

***Keywords*— Voltage regulation, reactive power control, reactors, wind inverters, power intermittency**

I. Introduction

It is common practice to operate each node of a power system at a designated voltage level. This is to ensure the power system equipment are supplied with input voltages at their rated values, within an acceptable tolerance limits [1]

Introduction of more and more renewable energy is a practice nowadays owing to environmental considerations. Even more countries are planning to use renewable power generation in the future. However, their intermittent nature will cause many problems in the power system, especially with respect to stability and power quality. Voltage management in networks is an important aspect under higher levels of grid connected distributed generation as intermittency in generation as well as fluctuations in demand may cause voltage and frequency problems in the system.

Some inherent properties of transmission lines also give rise to voltage complications. Ferranti effect is one such phenomenon taking place in power systems influencing bus voltages. Ferranti effect causes the voltage at the receiving bus of a power flow to have a higher voltage than the sending bus owing to low consumer demand at the power receiving end and the presence of a long transmission line with high capacitive properties increases the reactive power supply to the power system instead of absorbing reactive power.

Different methods to regulate the system voltage have been reported in the literature, basically, by controlling the reactive power with the aid of Flexible Alternating Current Transmission System devices (FACTS devices). Contemporary power systems use synchronous generators. capacitor banks, reactors, Static Var Compensators (SVCs), Unified Power Flow Controllers (UPFCs), Static Synchronous Compensators (STATCOM), Solid State Series Controllers (SSSC) [2] for this purpose. The ability of controlling reactive power from inverters has also been researched and practiced in this regard.

Management of network voltage through reactive power control with the grid connected wind farms is a relatively new topic for the Sri Lankan power sector. In Sri Lankan context, at present, reactive power is controlled by generator reactive power control (through excitation control using Automatic Voltage Regulators) and use of breaker switched capacitors (capacitor banks).

In this paper, design of an algorithm to control reactive power with the intension of maintaining voltage at specific voltage levels by optimally utilizing the limited resources such as reactors and inverters is discussed. The algorithm has the capability of responding to the variations from supply side (i.e. power generation) as well as from the demand side (i.e. customer usage).

As a case study, the control algorithm is applied on the reactive power resources in the transmission network of Northern region in Sri Lanka where the proposed Mannar Wind Power Plant will be integrated.

II. Voltage Regulation in Northern Region Transmission Network of Sri Lanka

Transmission network in northern region of Sri Lanka was chosen as the test environment to apply the developed control algorithm as a case study because of the complications prevailing at present as well as the additional complexities associated with the commitment to interconnect the proposed

100 MW Mannar Wind Power Plant (MWPP) to one of the remote ends of the transmission network.

Figure 1 shows the single line diagram of the study network of the northern region transmission network with proposed wind power plant.

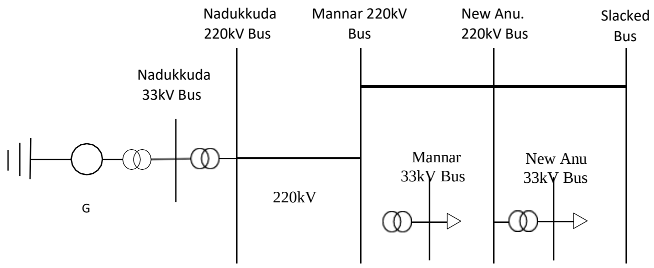

Fig. 1 - Single line diagram of study network

A. Complications due to system requirements

Currently, voltage at Anuradhapura, the strongest grid point in the Northern transmission network, is maintained at a slightly high level compared with other buses in the power system to meet certain system control requirements.

B. Problems owing to Ferranti Effect in the Northern Region transmission network

Transmission line between Mannar and Anuradhapura are longer in length (nearly 150 km) [3] while Mannar, the receiving end of power flows when the MWPP is not connected, is lightly loaded. Therefore, the voltage in Mannar is normally high due to Ferranti effect.

C. Problems owing to integration of the 100 MW Mannar Wind Power Plant

Mannar Wind Power Plant comprises 40 type IV wind turbines having a nominal capacity of 2.5 MW each (total capacity of MWPP is 100 MW) and with 40 transformers with voltage ratio of 690V/33 kV at each wind turbine. 33 kV power cables will be extended in a string configuration connecting each transformer to Nadukuda Grid Substation,

which is the collecting grid substation, where three transformers of voltage ratio 33 kV/ 220 kV will be installed to transfer the MWPP generation to the transmission network.

Connecting MWPP at Nadukuda, which is geographically and electrically close to Mannar causes the voltages of both the connecting point (i.e. Nadukuda) and Mannar to rise much higher than Anuradhapura, especially if MWPP at its full capacity of 100 MW. However, voltage at Nadukkuda cannot be higher than a certain level to ensure safety of the wind turbines. The intermittency of the power generation creates voltage fluctuations complicating the situation further.

D. Expected issues with future generation projections for Mannar Wind Power Plant

Further to the reported voltage complications, transmission network in Northern region together with the 100 MW wind power plant was simulated in Power system simulator for Engineering (PSS/E) under different study scenarios (power plant loading and customer load demands). Voltage complications in some selected buses in the study network were identified as given in Table 1.

- TABLE 1 - Future projected violated voltage levels

Generation level	GSS	If loads are tripped	For off peak load	For day peak load	For night peak load
Generation - 100 MW	Nadukkuda	1.069	1.069	1.068	1.068
	Mannar	1.069	1.068	1.067	1.067
	New Anu	1.053	1.053	1.053	1.053
Generation - 75 MW	Nadukkuda	1.069	1.068	1.067	1.067
	Mannar	1.069	1.068	1.067	1.067
	New Anu	1.053	1.053	1.053	1.053
Generation - 50 MW	Nadukkuda	1.068	1.068	1.067	1.067
	Mannar	1.068	1.067	1.066	1.066
	New Anu	1.053	1.053	1.053	1.052
Generation - 25 MW	Nadukkuda	1.067	1.067	1.066	1.066
	Mannar	1.067	1.067	1.065	1.065
	New Anu	1.053	1.053	1.053	1.052
Generation - 0 MW	Nadukkuda	1.066	1.066	1.064	1.064
	Mannar	1.066	1.065	1.064	1.064
	New Anu	1.053	1.053	1.052	1.052

III. Development of Voltage Control Algorithm

In the proposed control algorithm, the influence of reactive power on voltage is used as the key factor in regulating the voltage. Hence, by optimally controlling the reactive components of the system, the voltage regulation can be performed with the use of minimum network resources.

The algorithm applies a Gause Seidal iterative process to implement the node voltage method of power system analysis [4].

Nodal voltage method of power flow analysis.

$$I_i = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \qquad j \neq i$$

$$I_i = \frac{P_i - jQ_i}{V_i^*}$$

$$\frac{P_i - jQ_i}{V_i^*} = V_i \sum_{j=0}^{n} y_{ij} - \sum_{j=1}^{n} y_{ij} V_j \qquad j \neq i$$

Using Gause Seidal iterative method [4]

$$V_i^{(k+1)} = \frac{\frac{P_i^{sch} - jQ_i^{sch}}{V_i^{*(k)}} + \sum y_{ij} V_k^{(k)}}{\sum y_{ij}} \qquad j \neq i$$

A. *Reactive power control*

Since type IV wind turbine generators are used, the AC- DC-AC conversion process will be available at every wind turbine. Hence, the capability of controlling reactive power of those 40 inverters can also be included in developing the control algorithm.

It has been proposed to install two reactors in New Anuradhapura and Nadukuda, at 33 kV level at the respective grid substations with the integration of MWPP. The reactor at Nadukuda Grid Substation will have a capacity of 50 Mar which operates in 25 Mvar steps (i.e. 0, 25, and 50 Mvar). The reactor at New Anuradhapura Grid Substation will have a capacity of 100 Mvar which also operates in 25 Mvar steps (i.e. Level 0, 25, 50, 75, 100 Mvar).

The Old Anuradhapura bus will be acting as the infinite or the slaked bus bar where voltage and angle remain at the given reference, representing the rest of the system.

B. *Simulation Platform*

MATLAB/Simulink is selected as the platform to design and implement the controller. The test network included,

- 100 MW wind farm with inverters which are capable of generating and absorbing reactive power.
- Reactors which are capable of operating for a signal given by the controller to change the step of the reactor in order to absorb the required reactive power level. A 50 Mvar reactor (2 x 25 Mvar steps) in Nadukuda and a 100 Mvar reactor (4 x 25 Mvar steps) in New Anuradhapura.

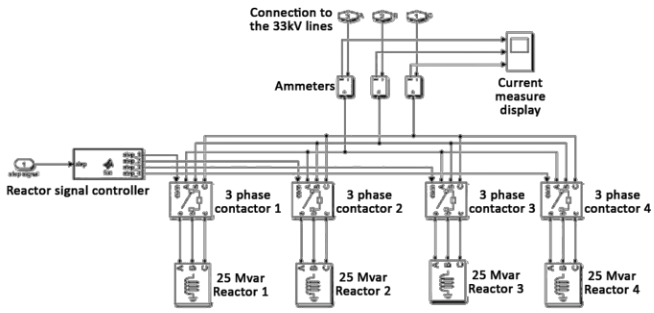

Fig. 2 - Step wise controllable reactor model

- The dynamic load which can vary active power, capacitive reactive power and inductive reactive power according to the load variation in the Northern region transmission network.

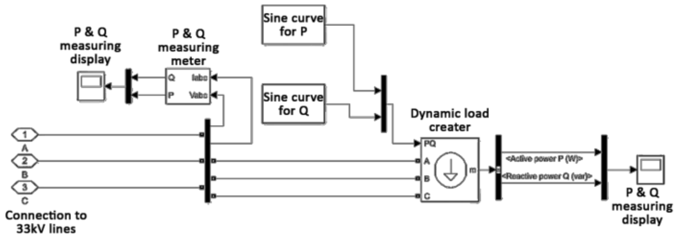

Fig. 3 - Dynamic load model

- Transmission lines from Anuradhapura to Mannar and Mannar to Nadukuda are modeled using pi (Π) transmission line model.
- Rest of the Sri Lankan power system is represented by an equivalent voltage source with effective impedance capable of generating the required amounts of active and reactive power to maintain the bus voltage at the desired level.

C. *Methodology and optimization*

Using the simulation platform described earlier, voltage combinations at specified buses with the engagement of available reactive power resources (reactors and invertors) were obtained for all possible reactive power absorption and/or injection levels. To find the optimal solution, the voltage combination with the minimum error with respect to the reference voltage level (i.e. 1 p.u.) was identified. In calculating the minimum error, the least of sum of squares method was used. (i.e. the square of the residuals; a residual being the difference between an observed value and the reference value of 1 p.u.).

With the aid of reactive power control capability of wind inverters (40 × 2.5 MW = 100 MW), it is suggested to control reactive power continuously. As the step of a reactor is 25 Mvar, reactive power control capability of wind inverters can be limited to a band of 25 Mvar. But an inverter is capable of absorbing and injecting reactive power. Therefore, total inverter reactive power controlling range is selected as ±12.5 Mvar.

Hence, the optimization was subjected to the constraints;

- 50 Mvar reactor in Nadukkuda which operates in 25 Mvar steps
- 100 Mvar reactor in Anuradhapura which operates in 25 Mvar steps
- 100 MVA (40 × 2.5 MVA) wind inverter capacity with continuous operation capability within a range of ±12.5 Mvar

The key requirement of the controller is to maintain the voltages of specified buses system requirements. According to the Grid Code of Sri Lanka, generating units need to operate and deliver the declared output within a voltage range of ±10% of the nominal voltage at the Connection point [5].

For the transmission system, the System Control Centre of the CEB will maintain all the network busses within following the voltage ranges.

TABLE II - Allowed voltage ranges for transmission lines

Bus Voltage (kV)	Voltage range	
	Normal operation	Under emergency
220	±10%	±10%
	198 kV to 242 kV	198 kV to 242 kV
132	±10%	±10%
	118.8 kV to 145.2 kV	118.8 kV to 145.2 kV
33	±2%	
	32.34 kV to 33.66 kV	

Though the minimum requirement is to maintain voltages at transmission buses (220 kV) within a voltage band of ±10%, it is envisaged to maintain all bus voltages at even a narrower band of ±5%.

Hence the algorithm checks whether the voltages are maintained as follows.

0.95 ≤ Voltage at New Anuradhapura 220 kV bus (p.u.) ≤ 1.05
0.95 ≤ Voltage at Mannar 220 kV bus (p.u.) ≤ 1.05
0.95 ≤ Voltage at Nadukkuda 220 kV bus (p.u.) ≤ 1.05

D. Features of the algorithm

- Ability to analyze any network

Even though Northern region transmission network of Sri Lanka is used as the simulation environment, the algorithm has been developed to extend the environment as required. Number of buses, number of customer demand points, number of generation points, and number of reactors or capacitor banks to be connected etc. can be changed as required in the algorithm.

- Ability to vary demand and generation

In a typical power system, instantaneous customer demand and power generation of renewable power sources will be varying with time. In the MATLAB model of the Northern region transmission network, variable demand is represented by a dynamic load model. Wind power output can also be varied for a particular state of pre-determined value of generation. The controller will acquire instantaneous values of demand and supply in the test network at the time of operation and it is capable of generating optimum reactive power generation or absorption for both varying demand and supply of power.

E. Flowchart of control algorithm

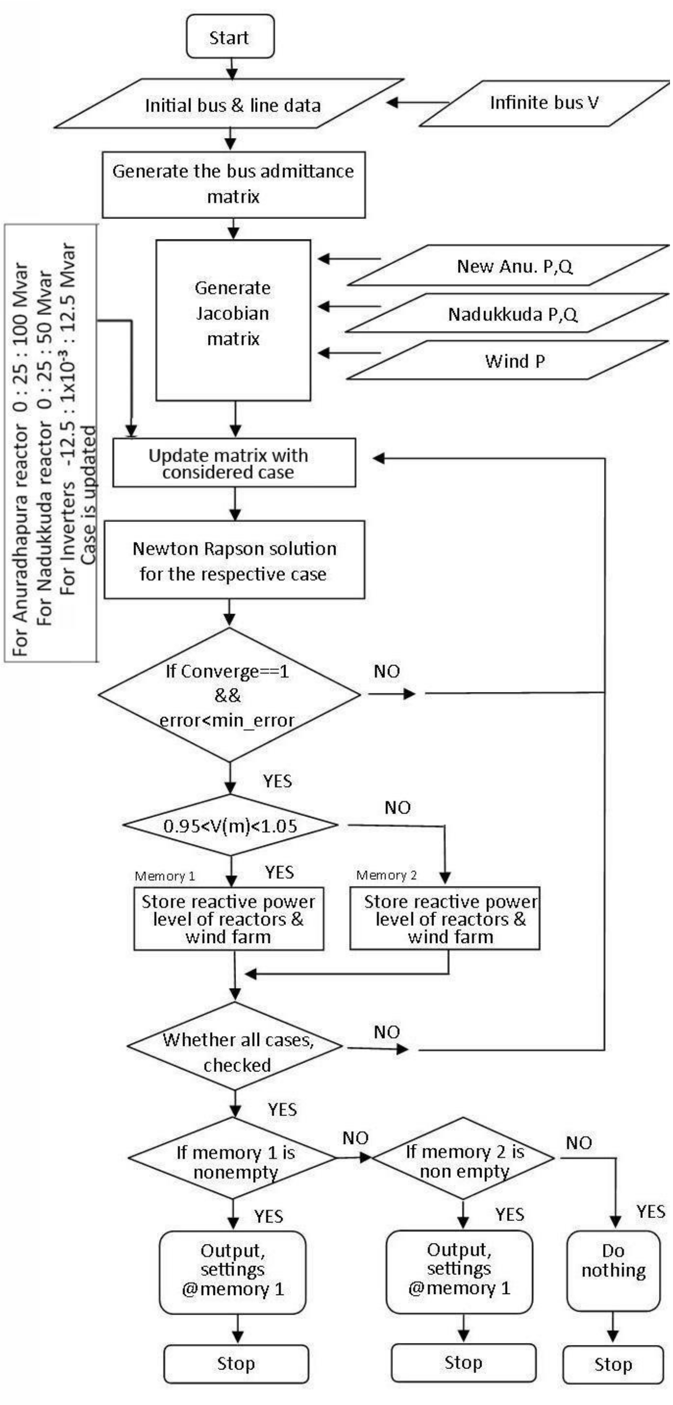

Fig. 4 - Flowchart of algorithm

F. Results and verification

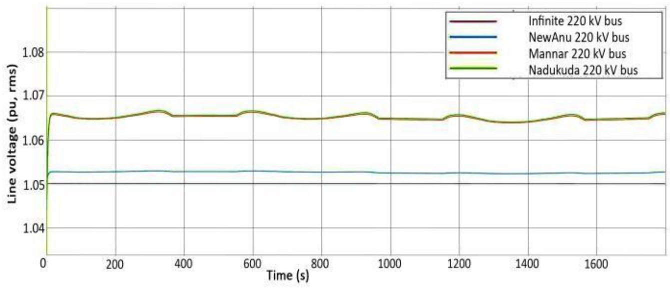

Fig. 5 - Voltage variation without the controller

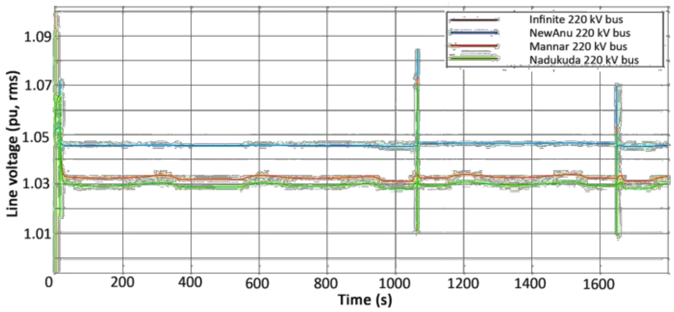

Fig. 6 - Voltage variation with the controller

As seen in the above graphs, it is very clear that when the slack bus is maintained at 1.05 p.u., the rest of the buses in the considered system reach voltages higher than 1.05 p.u. which is an undesirable situation. But, once the controller is connected, the voltages remain between 0.95 and 1.05 regardless of the variations in power generation and customer demand.

The results obtained MATLAB/Simulink simulation platform was further verified with several test cases using the previously described PSS/E model, thus the performance of the control algorithm can be considered suitable for power system applications.

IV. Conclusion

Regulating bus voltages within specified narrow ranges is important while intermittent nature of the renewable power sources and varying customer demand makes this task extremely difficult. The control algorithm presented in this paper is capable of using the available reactive power resources such as reactors and inverters optimally to maintain system voltages within specified voltage levels.

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