Distributed Control for Effective Grid Operation with High Penetration of Renewable Generation (ICMEPE-2016)

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Abstract. In this paper, we consider the problem of effective grid operation with high penetration of renewable energy sources. In spite of the fact that such sources are naturally distributed and intermittent, the generation and consumption must be balanced in real time and the voltage has to conform to certain standards. At the same time, it is required to minimize the cost of energy. This is the goal that can be solved using optimal control techniques that in turns calls for a network of communication lines that carries a sizable cyber cost. In attempt of solving these problems it is proposed to use suboptimal supervisory control with Local Distributed Control Systems (LDCSs) placed at local Points of Common Coupling (PCCs) along with the partition of a distribution system into control areas receiving decision vectors from the supervisory system level. The LDCS reduces power losses by providing necessary reactive power at the point of load that results in fast dynamic stabilization of the voltage and consequently in an increase of renewable energy that could be delivered to grid. The use of photovoltaic (PV) generators and/or battery banks connected to inverters that run special control algorithm is proposed to implement the LDCSs. Such LDCS regulates the voltage and can provide or absorb both the real and the reactive power.

To simulate distribution system, in order to investigate its operation, proposed are certain modification of RPM-Sim simulator developed at the National Renewable Energy Laboratory (NREL), Golden, Colorado. The simulator's modified design, proposed in the paper, is presented in details and can be used in the development and testing of supervisory control of grids with renewable energy sources. In addition, the principles of distributed suboptimal operation of power distributed systems are formulated.

Key words

renewable generation, supervisory distributed control, suboptimal grid operation, distribution system simulation.

1. Introduction

Renewable energy sources are naturally distributed and intermittent, so high penetration challenges effective grid operation since generation and consumption must be balanced in real time, and voltage must be maintained within the standard anywhere anytime. When voltage transients exceed allowable limits, renewable generators are disconnected resulting in revenue loss from increased maintenance and reduced generation. This is more severe in wind farms due to rapid changes of wind speed and direction. The electric grid is a large passive network that becomes hypersensitive with high penetration of renewable generation. In such network, properly controlled fast actuators have to be added at local points of common coupling (PCC) in order to overcome the effects of local transients. In particular, extremely rapid reactive power control is necessary to minimize the voltage flicker and to mitigate sags, swells, and other rapid weather-induced voltage changes so that PCC voltages are held within the limits set by a top-level supervisory controller. Distributed control systems, placed at local PCCs should increase grid reliability/stability to enable increased penetration of renewable generation.

The simulation results from a model of the wind/solar generation and distribution system developed using RPM-Sim simulator [2, 3] can be compared with power quality measurements from the site coupled to measured wind inputs. The model will guide number, placement, and set points of Local Distributed Control Systems (LDCSs) necessary to stabilize the system voltage. Successful execution will demonstrate that extremely dynamic distribution networks can be stabilized using distributed LDCSs, providing evidence that high renewable energy penetration can be realized with increased up-time of renewable generators.

A bi-level control system is considered, in which the top-level supervisory controller executes long-term tasks and manages system-wide power flow based on sensed PCC voltages. The LDCS can be programmed to realize grid optimization according to a set of given objectives such as: increased renewable energy penetration, improved efficiency, and improved availability.

Summarizing, we can say that we have to solve a problem of proper grid integration of Distributed Generators (DGs) which, if properly integrated will result in two main advantages:

- will help to decongest existing transmission grids;

- with DGs based on renewable (wind and solar) emissions are reduced.

Photovoltaic (PV) generation is a key technology for realizing the distributed generation concept. One of the most important problems to be solved in order to realize mentioned above goals is the development of advanced control strategies for power-electronic devices interfacing PV systems with the grid and system-level or supervisory optimal dispatch strategies[2,6,7]. One of the basic problems is the efficiency increase through enhancing of the power extraction process due to reliable irradiance estimation. PV generators, through the injection of reactive power, can provide steady-state voltage regulation, and fault-ride-through (FRT) capabilities to be used for dynamic grid support [7].

The goal of this paper is to report the necssary modifications of the RPM-Sim simulator [3-6], introduced to facilitate the simulation study of various aspects of operation of a distributed suboptimal voltage control system to be developed for improvement of power grid operation.

2. LDCS Goals and Expected Benefits of Improved Grid Operation

The LDCS has fast local autonomous reactive power control capability to stabilize the PCC voltage to follow a voltage reference set by the top-level supervisory controller. Line voltage is sensed at the point where the LDCS connects to the grid and the local control action stabilizes the sensed voltage to the desired set point. Since the voltage specification is given with upper and lower limits, the LDCS can be programmed to realize fast stabilization of the PCC voltages without exceeding the limits during any transient. The LDCS can also be programmed to slowly adjust the grid voltage profile inside the voltage band and minimize the reactive current flow resulting in the minimization of the power losses in the line during the steady state or slow variations. Reducing system losses associated with the transmission of reactive power is equivalent to reducing the electricity generation needed during times of peak demand. Actively stabilizing the voltage profile extends the margin to voltage collapse to help prevent grid outages, therefore improving grid up-time. In addition, the top-level supervisory control can be programmed to direct the traffic from congested lines to lightly loaded lines to further prevent outages.

Since the voltage rating is specified over an acceptable range, voltage regulation loop error is allowed by using a low feedback gain as long as the error is within the limits. The advantages of this design include increased phase margin for the regulation loop, less curtailment, and a momentary active power insertion or extraction. The increased phase margin directly contributes to loop stability. Less curtailment is granted by allowing a greater voltage deviation during the transient. The momentary active power insertion and extraction can be helpful for enhanced voltage support.

In the event of an unintentional “island” caused by a partial grid failure, or an intentional “island” creation for other reasons, a smaller grid is resulted with significantly higher dynamic than the original larger grid, since load and generation transients are likely to be a larger percentage of the total “island” power rating. The widely distributed LDCSs that become part of the island are now present to compensate the more dynamic system to maintain “islanded” micro-grid stability and provide improved reliability services for the “islanded” loads. When the “island” is reconnected to the main grid, the resulting voltage transients will also be rapidly mitigated to help prevent damage to loads and equipment.

The LDCS reduces power system losses by providing necessary reactive power at the point of load to reduce the reactive power that must be carried by the power distribution network. Removing reactive power from the distribution network frees up valuable capacity in substations, cables, breakers, and transformers so that it can be used to deliver an increased fraction of usable power. The LDCSs therefore increase the asset utilization to achieve an increased load factor. Furthermore, the enhanced stability of the network and the increased margin to voltage collapse directly translates to improved system operation and resilience to enable increased system loading.

In reference [1], two voltage control strategies are compared: curtailment and voltage regulation through the reactive power compensation. The results showed that active voltage regulation resulted in an increase in the amount of renewable energy that could be delivered to the grid. Therefore, a LDCS that provides fast dynamic stabilization of the voltage should reduce the need for curtailment, so that more renewable energy can be delivered to the grid.

These top-level voltage regulation schemes can be explored in the RPM-Sim modeling environment to determine the desired voltage-profile set points based on the grid configuration and the distribution of sources and loads within the grid and evaluate metrics by which these may need to be adjusted or varied in time to optimize system-level operation. Initially, this could be done for the wind-farm extremely dynamic high-penetration environment that provides an excellent field test challenge and later the results could be generalized to the greater grid.

The approach of local fast, independent “autonomous” control of voltage using numerous LDCSs, combined with a top-level set-point control for coordination, provides a resilient architecture. This distributed autonomous architecture makes fast control possible to stabilize the grid in real-time without the need for high-speed, wide-spread communication which is costly to install, maintain, and operate; low-speed (once every 10 minutes or more) update of the LDCS set points should be more than adequate for coordination. A solid foundation of autonomous distributed reactive power control not only improves the performance, efficiency, and reliability of the distribution system but also provides solid building blocks that simplify system-level operation and control. It results in reduced operating costs.

3. Distributed Suboptimal Operation of Power Distribution Systems

The main goal of Distribution Management Systems (DMSs) is to maintain reliability of power distribution systems. They provide supervisory control commands based on real-time status of the distribution system. The new capabilities for supervisory control are created by the integration of renewable-based small local generators or Distributed Generators (DGs). These generators can support local control system needs and goals and be interfaced to the grid by power converters with fast continuous control capabilities that could be exploited by DMSs in order to implement dispatch algorithms. These algorithms should be based on optimal power flow model and are expected to maintain required power quality and minimize energy costs.

It should be noticed that exploiting the control capabilities of local power converters at the system level increases significantly the requirements on the supporting cyber structure. In the attempt for solving this problem it is proposed [7] to partition a distribution system into control areas. Each control area, while exchanging limited amount of information with its neighbors, would be locally optimizing its converters' settings in order to pursue system-level goals of sub-optimal control.
These suboptimal control goals at the node *j*, within each control area, can be represented by the decision vector

$$d_j = [I_{jk}\ V_j\ P_{jk}\ Q_{jk}\ p_j^g\ q_j^g]$$

where

- V_j - voltage at node *j*
- I_{jk} - current through the branch series impedance connecting node *j* to node *k*
- P_{jk} - real power flowing through a branch series impedance connecting node *j* to node *k*
- Q_{jk} -reactive power flowing through a branch series impedance connecting node *j* to node *k*
- p_j^g - real power generated by node *j*
- q_j^g - reactive power generated by node *j*

In addition, the following denotations are introduced:

- N - set of control areas that contains all nodes in a distribution system
- $N^{(i)}$ - control area *i*
- $\overline{N}$ - number of control areas

Then

$$N^{(i)} \in N, i = 1,2,..., \overline{N}.$$

The control system at the level of the DMS sets suboptimal goals for each control area by specifying and updating the control area-specific decision vectors. Then, the control area's control system, subject to the received decision vector, minimizes the generation cost by setting for each node in its area the decision vector d_j defined above so that the following control area cost function is minimized:

$$\min_{j \in N^{(i)}} \sum_j p_j^g(d_j)$$

subject to

$$V_k = V_j - Z_{jk} I_{jk},$$
$$P_{jk} + jQ_{jk} = V_j I_{jk}^*,$$
$$p_j^g - p_j^d = \sum_{k:j\to k} P_{jk} - \sum_{i:i\to j} (P_{ij} - P_{ij}^{losses}),$$
$$q_j^g - q_j^d = \sum_{k:j\to k} Q_{jk} - \sum_{i:i\to j} (Q_{ij} - Q_{ij}^{losses}),$$
$$|V_{\min}|^2 \le |V_j|^2 \le |V_{\max}|^2,$$
$$p_{j,\min}^g \le p_j^g \le p_{j,\max}^g,$$
$$q_{j,\min}^g \le q_j^g \le q_{j,\max}^g$$

where Z_{jk} is the branch impedance between nodes *j* and *k*, $*$ denotes conjugate, and the generated and demanded powers at node *j*, are respectively denoted by p_j^g, p_j^d. Similar is the denotation of reactive powers q_j^g, q_j^d. Above we have four equations: Ohm's law, calculation of real and reactive power transferred through the branch between nodes *j* and *k*, real power balance, and reactive power balance, both calculated at node *j*. These equation are followed by lower and upper bounds of $|V_j|^2$, p_j^g and q_j^g.

4. Implementation of the LDCS in the RPM-Sim Environment

The LDCS in the RPM-Sim environment is implemented using inverter module that runs special control algorithm. The inverter is connected to the DC bus supplied by the battery and/or the PV array. The voltage command V_{ref} from the top-level supervisory control gives the set point of the grid voltage at PCC. The voltage feedback signal V_{PCC} is compared with the V_{ref} to generate an error signal. This error signal serves as input to a controller, which generates the reactive current I_{qINV} injected into the local PCC. Due to the injection of the I_{qINV}, the grid voltage at PCC is influenced. Depending on the location of the PCC, the grid voltage response to the I_{qINV} injection can be very different. Simulation can be conducted to select the best location for reactive current injection. The proposed LDCS injects or absorbs reactive power in fast response to local-control commands to dynamically stabilize the electrical grid. It also allows for momentary real power insertion and extraction to help for enhanced voltage support. The proposed LDCS that serves a particular control area is a system of widely distributed voltage compensation nodes that dynamically stabilize the voltage profile to enable high penetration of renewable energy.

The original inverter, included in the RPM-Sim, can operate in the master or slave mode [6]. In the current application, the master mode is used, in which the inverter regulates the voltage and if connected to a battery bank can provide or absorb both the real and the reactive power. However, in conjunction with the PV array, the inverter can supply real power and provide or absorb reactive power. In master mode of operation, the power exchange is determined by the system's power balance.

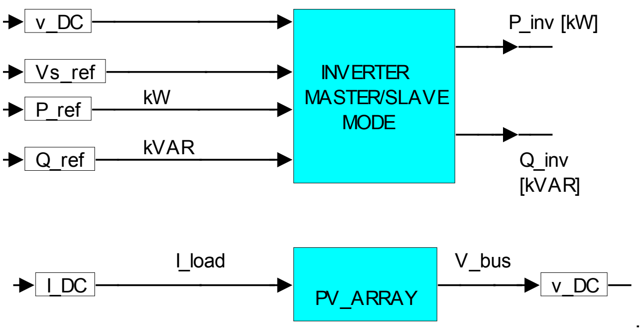

Fig.1 Inverter in master mode in conjunction with PV array

The configuration considered is shown in Fig.1. Note that the inputs P_ref and Q_ref are not used in the master mode.

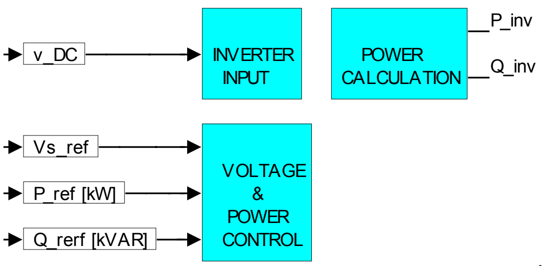

Fig.2 Inverter expansion: principal functional modules

In Fig.2, the inverter's principal functional modules are shown with expanded inverter input in Fig.3, voltage control in Fig.4, and power calculation in Fig.5. The inverter has two outputs: (1) the actual real power provided or absorbed P_{inv} and (2) the actual reactive power provided or absorbed Q_{inv}. . In the master mode, these variables assume the values, which are the consequence of the power balance in the simulated system. In Fig.3, we show the inverter input module. In this figure, the equivalent circuit diagram (a) clarifies the simulation diagram (b). Assuming that the inverter's real power, provided or absorbed, is known, we calculate the DC current I_{DC} drawn from or provided to the DC source.

The inverter current components contributed at the PCC in the master mode are generated in Q- and D-generator, which are presented in Fig.4. First, the controller generates the electromotive force

$$E_{q\_I} = K_e v_{DC} ,$$

which is required at the given load to maintain the system's voltage. This value of E_{q_I} is used in the Q-generator to generate the q-component of the current

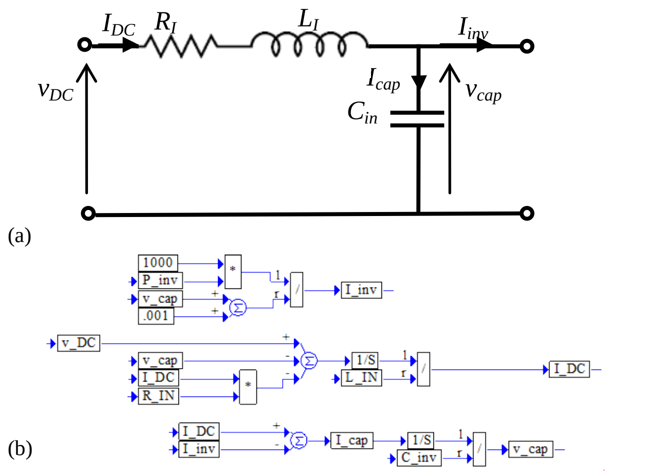

Fig.3 Inverter input module: (a) equivalent diagram, (b) simulation diagram

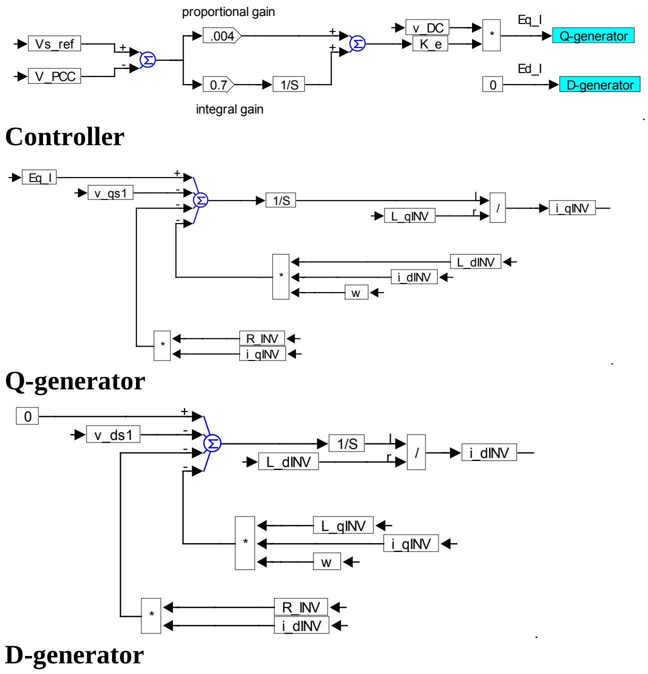

Fig.4 Master mode operation of the inverter's voltage control module

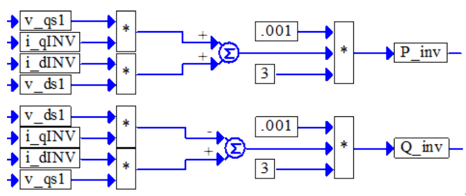

Fig.5 Inverter's power calculation module

contributed at the PCC by the inverter operating in the master mode. In this figure, we also have the D-generator, whose input equals zero. This is the consequence of the assumed reference frame.

In Fig.5, we show the simulation diagram of the power calculation module of the inverter. Using current components I_{q_INV} and I_{d_INV}, determined as shown in Fig.4, we calculate in this simulation diagram the real power P_{inv} and the reactive power Q_{inv}. The voltages v_{qs1} and v_{ds1} are defined in the circuit diagram of the PCC module in Fig.6.

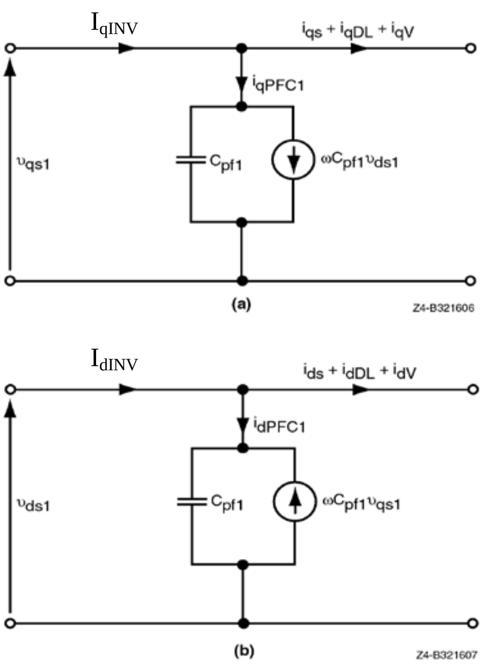

Fig.6 PCC module circuit diagram: (a) q-axis, (b) d-axis

The circuit diagram in Fig.6 also explains the simulation diagram of PCC shown in Fig. 7. Note that if the current representing a given module enters the top node in the circuit diagram of Fig.6 (or is added at the summing junction in Fig.7), its power is positive when it is generating power and negative when it is absorbing power. On the other hand, if the current representing a given module leaves the top node in the circuit diagram of Figure 6 (or is subtracted at the summing junction in Fig.7), its calculated power is positive when it is absorbing power and negative when it is generating power. To follow the general convention that the power generated is positive and the power absorbed is negative, we invert the sign of the power calculated for the modules represented by the currents leaving the top node in the diagram shown in Figure 6 that defines

$$i_{qPFC1} = i_{qINV} - i_{qs} - i_{qDL} - i_{qV},$$
$$i_{dPFC1} = i_{dINV} - i_{ds} - i_{dDL} - i_{dV}.$$

Using the same circuit diagram, we write the following equations defining q-axis and d-axis components v_{qs1} and v_{ds1} of the line voltage (V_{PCC}):

$$v_{qs1} = \frac{1}{C_{pf1}} \int (i_{qPFC1} - \omega C_{pf1} v_{ds1}) dt,$$
$$v_{ds1} = \frac{1}{C_{pf1}} \int (i_{dPFC1} + \omega C_{pf1} v_{qs1}) dt,$$

where C_{pf1} is the PFC capacitor of the value to be designated by the user, and ω is the real system frequency controlled by the inverter. These equations are implemented as shown in Fig.7. V_{PCC} is calculated in the compound block V_meter, shown in Fig. 7, according to the following equation:

$$V_s = \sqrt{v_{qs1}^2 + v_{ds1}^2}.$$

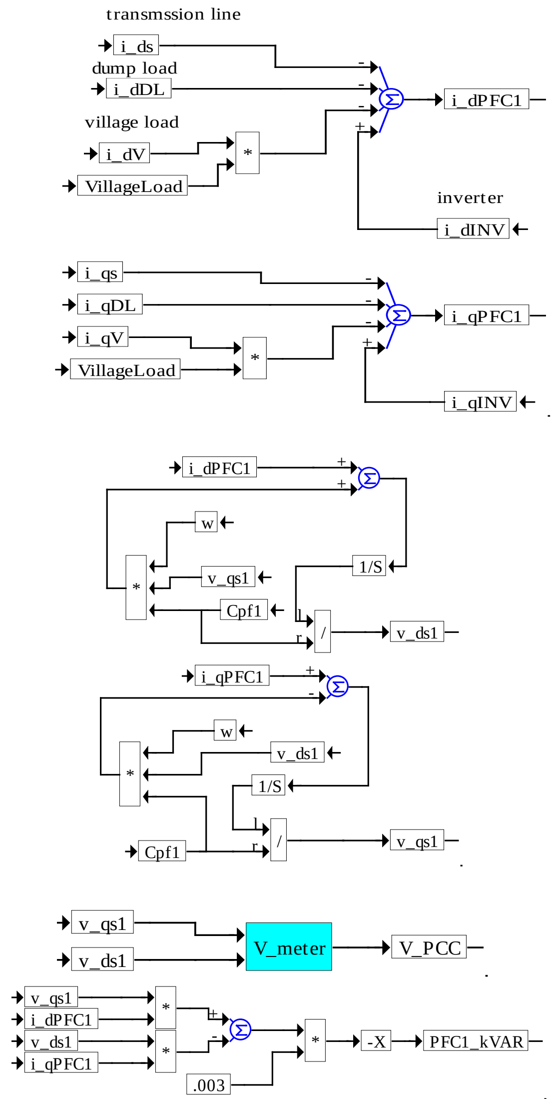

Fig.7 PCC module simulation diagram: summing junction for d-axis and q-axis currents, generation of d and q components of V_{PCC}, calculation of the system voltage V_{PCC} and the reactive power generated by the PFC capacitors.

The calculation of the reactive power generated by the PFC capacitor is also shown in Fig.7. According to our convention, the reactive power generated must be positive. If the power is generated, the currents i_{qPFC1} and i_{dPFC1} should be entering the summing junction. It may be checked that the currents are leaving the junction. In other words, the calculated reactive power is negative, so we introduce the inversion of sign in the calculation of the reactive power as shown in Fig.7. In this figure Village Load is a binary variable (to be programmed) that allows to connect or disconnect village load from the system.

5. Conclusion

The problem of effective grid operation with high penetration of renewable energy sources was considered. Power generation (of required quality) and consumption has to be balanced and the cost of energy has to be minimized. To solve this problem, we proposed the suboptimal supervisory control with Local Distributed Control Systems (LDCSs) placed at local Points of Common Coupling (PCCs) along with the partition of a distribution system into control areas receiving decision vectors from the system's supervisory level. Considering the received control vector, the control system of each control area develops suboptimal control vectors for all nodes in its area.

In the paper, the implementation of the LDCS in RPM-Sim environment is proposed. It uses properly modified, inverter module of the RPM-Sim. The proposed LDCS injects or absorbs reactive power in fast response to local control commands to dynamically stabilize the electrical grid. It also allows for momentary real power insertion and extraction to help for enhanced voltage support. The proposed LDCS that serves a particular control area is a system of widely distributed voltage compensation nodes that dynamically stabilize the voltage profile to enable high penetration of renewable energy.

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