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SCADA Implementation of Secondary Voltage Control and Active Power Monitoring of AC Microgrid using SIEMENS SIMATIC S7 300 PLC and Totally Integrated Automation (TIA) Portal

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Abstract

This paper presents secondary voltage control and active power monitoring of Microgrid system using Supervisory Control and Data Acquisition (SCADA) system. Distributed co-operative control algorithm is used for the secondary voltage control and load sharing among participating DGs in the Microgrid. The distributed co-operative structure of Microgrid removes the requirements for a central controller and complex communication network used in centralized structure of Microgrid, in turn, improves the system efficiency and reliability. The SCADA system allows to study and implement the control scheme of the Microgrid and also it offers effective methods for improving the control systems, equipment performance and management of distributed generators (DGs).

Keywords: *Microgrid, SCADA, PLC, Active Power*

1. Introduction

In India, the electric grid consists of transmission and distribution networks that have been developed over a hundred years. Most of the electricity is currently delivered from large generation plants located hundreds of miles from load centers through large interconnected transmission networks to substations that subsequently distribute power to various residential, commercial, and industrial loads. This ensures that electricity is generally delivered with a high reliability and at a low cost due to the economics of scale. However, there are cases where customers do not have highly reliable and low cost energy. In particular, the customers located in remote locations or that have experienced a natural disaster are the prime examples of deprived people. This has resulted in a lower quality of life and economic issues. Microgrid as the name implies, small networked electric grids with additional capabilities. The Microgrid utilizes any combination of local generation and energy storage to supply local needs. It has the ability to disconnect from a main delivery system if one exists (islanding), and also seeks to interact with other interconnected electric systems. Microgrid have been a developing area of research and are becoming an increasingly important discussion topic with distributed generation [1]-[2]. Proper control of Microgrid is essential requirement for stable and economically efficient operations of smart grids [5], [6]. Microgrids can operate in both grid-connected and islanded operating modes. In normal operation, the Microgrid is connected to the main grid. In the event of a disturbance, the Microgrid disconnects from the main grid and enters in to the islanded operation. Once a Microgrid is islanded, the so-called primary control maintains the voltage and frequency stability [6]-[10]. How-ever even in the presence of primary control, voltage and frequency can still deviate from their nominal values due to perturbation in the other DGs connected. To restore the voltage and frequency of DGs to their nominal values, the secondary control is also required [6],[7],[11],[18].

Conventional secondary controls of Microgrid assume a centralized control structure that requires a complex communication network [6],[7],[12], in some cases, with two-way communication links [11]. This can adversely affect the system reliability. Alternatively, distributed cooperative control structures with sparse communication network are suitable alternatives for the secondary control of Microgrid. Distributed co-operative control is recently introduced in power systems [19] to regulate the output power of multiple photovoltaic generators.

Over the last two decades, networked multi-agent systems have earned much attention due to their flexibility and computational efficiency. These systems are inspired by the natural phenomena such as swarming in insects, flocking in birds, thermodynamics laws, and synchronization and phase transitions in physical and chemical systems. In these phenomena, the co-ordination and synchronization process necessitates that each agent exchange information with other agents according to some restricted communication protocols [20],[23].

In this paper, distributed co-operative control of multi-agent systems proposed in [1] to implement the secondary voltage control of Microgird. The term distributed means that the controller requires a communication network by which each agent receives the information of its neighboring agents only. The term co-operative means that, in contrast to the competitive control, all agents act as one group towards a common synchronization goal and follow co-operative decisions [20]-[24]. Distributed co-operative control of multi-agent systems is mainly categorized into the regulator synchronization problem and the tracking synchronization problem. In regulator synchronization problem also called leaderless consensus, all agents synchronize to a common value that is not prescribed or controllable. Distributed cooperative control for multi-agent systems with nonlinear or non-identical dynamics has been recently introduced in the literature [9]

Considering DGs in Microgrid as agents in a networked multi-agent system, the secondary control design resembles a tracking synchronization problem. The dynamics of DGs in Microgrid are nonlinear and non-identical; input-output feedback linearization is used to transform the nonlinear heterogeneous dynamics of DGs to linear dynamics. Thus, the secondary voltage control is transformed to a second-order tracking synchronization problem.

In this paper, distributed cooperative control of multi-agent systems is adopted for SCADA implementation of the secondary voltage control scheme for Microgrid system. The salient features of the control methodology used here are:

- The secondary voltage control of Microgrid is implemented using distributed co-operative control of multi-agent systems.
- Input-output feedback linearization is used to solve the tracking synchronization problem for nonlinear and heterogeneous multi-agent systems.
- The secondary voltage control removes the requirement for a central controller and requires only a sparse communication structure with one-way communication links which is cheaper and can be more reliable.
- Desired response speeds can be obtained by tuning the controller parameters.
- The SCADA system used for monitor and acquisition of large data as well control scheme implementation in the distributed structure.

The paper is organized as follows. In Section II, overview of SCADA systems in general is discussed. The section III discusses the primary and secondary control levels for Microgrid. In Section IV, secondary voltage control based on distributed co-operative control is revisited. In Section IV, input-output feedback linearization is adopted to design a secondary voltage control. The SCADA implementation of secondary control is presented in Section V for Microgrid test system. Section VI concludes the paper.

2. Overview of SCADA System

The SCADA system has ability to handle a large number of data in real time and measure information of the different instruments to ensure monitoring and acquisition of data in a database [15]. Basically, SCADA application consists of two blocks: The first block is used for monitoring and control of the process system machinery. For instance, a powerhouse, telecommunication central, isolated sites (Mining sites, Wind Parks), factory, control and monitoring networks (water, gas, electricity), unity of refining and oil transportation, a system of traffic lights, etc... The second element is a network of smart devices to process the data acquired from the first element via sensors and control outputs. This will allow the SCADA system to measure, control and display the real-time state of elements of the first block [16]. Indeed, the SCADA system is complete manager of variables and indicators. This system is the core of various modules which communicates between them by using different communication protocols to assure the supervision, control and data acquisition as depicted in Fig. (1)

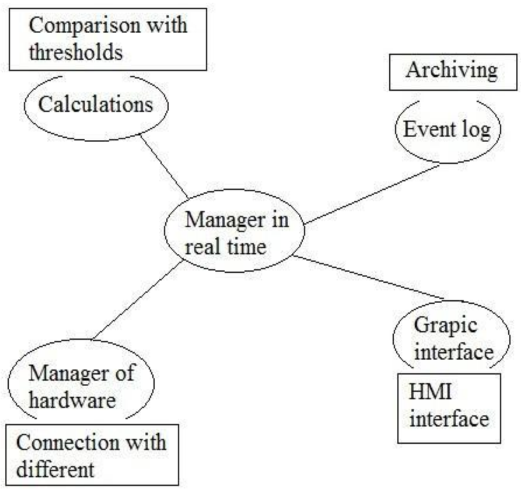

Fig. 1. Software organization of the supervisor

3. Review of MICROGRID Controller

A.Primary Control

The primary control is usually implemented as a local controller at each DG. This control level always exists and takes action in the event of disturbances. The coordinated control of the primary local controllers can be achieved by the active and reactive-power droop techniques [6],[7]. Droop technique prescribes a desired relation between the frequency and active power *P* & between the voltage amplitude and reactive power *Q*. The frequency and voltage droop characteristics for the DG are given by

$$\omega = \omega^{*} - D_p P \qquad (1)$$

$$E = E^{*} - D_Q Q \qquad (2)$$

Where *E* is the reference value for the output voltage magnitude that is provided for the internal voltage control loop of DG, ω is the angular frequency of the DG dictated by the primary control, *P* and *Q* are the measured active and reactive power at the DGs terminal, D_P and D_Q are the droop coefficients, *E* and ω are the primary control references [6], [7]. The droop coefficients are determined based on the converter power rating and the maximum allowable voltage and frequency deviations. The secondary control sets the references for the primary control *E* and ω in (1) so as to regulate the frequency and voltage amplitude to their prescribed nominal values. Conventionally, the secondary control is implemented for each DG using a centralized controller having the proportional-plus-integral (PI) structure [6], [7]. This secondary control is centralized and requires a star communication structure. In a star communication structure, it is necessary to have a communication link between all DGs and the central controller. Due to the centralized structure of this controller, this control scheme can potentially be unreliable. Alternatively, a distributed cooperative control structure is used in this paper [1].

B. Secondary control

The secondary voltage control is designed based on the large-signal nonlinear dynamical model of the DG [9]. The block diagram of an inverter-based DG is shown in Fig. (2). It contains an inverter bridge, connected to a primary dc power source (e.g., photovoltaic panels or fuel cells). The control loops, including the power, voltage, and current controllers, adjust the output voltage and frequency of the inverter bridge [9].

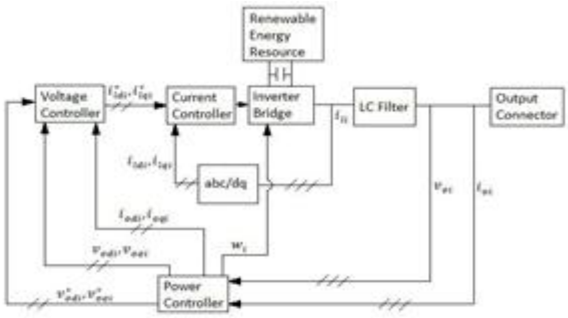

Fig. 2. Block diagram of an inverter-based DG

4. Distributed Cooperative Control for Secondary Voltage Control

Microgrid resembles a nonlinear and heterogeneous multi-agent system, where each DG is an agent. The secondary control of Microgrid is a tracking synchronization problem where all DGs try to synchronize their terminal voltage amplitude to pre-specified reference values. For this purpose, each DG needs to communicate with its neighbors only. The required communication network can be modeled by a communication graph [9]. Firstly, a preliminary on the graph theory used is presented. Then the secondary voltage control is implemented through input-output feedback linearization and distributed cooperative control of multi-agent systems. Finally, the communication network requirements for the proposed secondary voltage control are discussed.

A. Preliminary of Graph Theory

The communication network of a multi-agent cooperative system can be modeled by a directed graph (digraph).

A digraph is usually expressed as $G_r = (V_G; E_G; A_G)$ with a nonempty finite set of *N* nodes $V_G = v_1; v_2; ; v_N$, a set of edges or arcs $E_G V_G \times V_G$, and the associated adjacency matrix $A_G = [a_{ij}] \epsilon R^{N \times N}$. In Microgrid, DGs are considered as the nodes of the communication digraph. The edges of the corresponding digraph of the communication network denote the communication links.

In this paper the digraph is assumed to be time invariant *i.e.* *A+G* is constant. An edge from node *j* to node *i* is denoted by $(v_j; v_i)$ which means that node *i* receives the information from node *j*, a_{ij} is the weight of edge $(v_j; v_i)$ and $a_{ij} \leq 0$ if, $(v_j; v_i) \epsilon E_G$ otherwise $a_{ij} = 0$. Node *i* is called a neighbor of node *j* if $(v_i; v_j) \epsilon E_G$. The set of neighbors of node *j* is denoted as $N_j = \{(v_i; v_j) \epsilon E_G\}$ For a digraph, if node *i* is a neighbor of node *j* then node *j* can get information from node *i* but not necessarily vice versa. A digraph is said to have a spanning tree if there is a root node with a direct path from that node to every other node in the graph [24].

B. Co-operative Secondary Voltage Control Based on Feed-back Linearization and Tracking Synchronization Problem

The dynamics of DGs in Microgrid are nonlinear and may be non-identical. Therefore, the secondary voltage control resembles the tracking synchronization problem of a multi-agent system with nonlinear and non-identical dynamics. To design a distributed secondary voltage control, the tracking synchronization problem for a nonlinear and non-identical multi-agent system must be solved. In a distributed control structure each DG is allowed to communicate with its neighbors only. As mentioned above the required communication network can be modeled by a communication graph. Input-output feedback linearization can be used to facilitate the secondary voltage control design. In input-output feedback linearization, a direct relationship between the dynamics of the output y_i (or equivalently v_{odi}) and the control input u_i (or equivalently E_i) is generated by repetitively differentiating y_i with respect to time [23]. The block diagram of secondary voltage control based on distributed cooperative control is shown in Fig. (3).

5. CASE STUDY

The effectiveness of the proposed secondary voltage control is verified by simulating Microgrid in SCADA system. Fig. (4) illustrates the single-line diagram of the Microgrid test system consists of four DGs.

Siemens SIMATIC S7 300 controller and totally integrated automation (TIA) portal is used for design of Microgrid and implementation of secondary level distributed co-operative control of the multi-agent system.

A. TIA portal

The Totally Integrated Automation (TIA) portal provides unrestricted access to complete range of digitalized automation services from digital planning and integrated engineering to transparent operation. With the TIA Portal one can integrate not only the basic software but also the new functionalities like multiuser and energy management in a single interface. The individual components of the complete software package are closely linked. As a result, the TIA Portal offers a variety of functions that link automation and digitalization in a way that is both efficient and most importantly manageable. The TIA Portal allows to integrate all the key components like control, HMI, drives, decentralized peripherals, motor management, and power distribution.

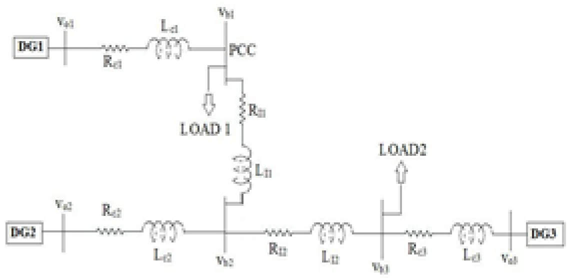

Fig. 3. Block diagram of the secondary voltage control

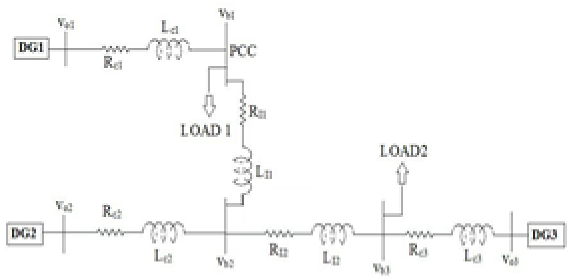

Fig. 4. Single-line diagram of the Microgrid test system

B. SIMATIC S7 300

The main features of SIMATIC S7 300 are as under:

- It is modular mini Programmable Logic Controller (PLC) system for the low and mid-performance ranges. With comprehensive range of modules for optimum adaption to the automatic task.
- Flexible use through simple implementation of distributed structures and versatile networking.
- Module mounting: Simply hang the modules on the mounting rail, swing them into place and screw into position.
- Integral backplane bus: The backplane bus is integrated into the modules. The modules are connected via bus connectors plugged into the rear of the housings.
- Simple replacement of the modules with mechanical key coding: Only the fixing screw of the modules has to be unscrewed to replace the module. Wired front connectors are easy to release by pressing on the locking mechanism. The front connector coding prevents connection of the wired front connector to the wrong module type.
- TOP Connect: This offers pre-assembled wiring with 1-core to 3-core connections and screw-type or spring-loaded terminals. Alternative to wiring direct on the signal module.
- Defined installation depth: All connections and connectors are recessed into the modules and protected and covered by front doors. All modules thus have a defined installation depth.

- No slot rules: Signal modules and communications processors can be connected in any way without restrictions. The system configures itself.

C. Model

To implement the Microgrid control structure using SCADA system, firstly the main screen which contain all the DGs, local loads and connection to the utility grid are designed as depicted in Fig. (5).

Fig. 5. Microgrid system with SCADA

The SCADA system shown in Fig. (6) contains solar cell with the inverter system and generated power which will be first convert into AC supply which will inject power into the transmission line with use of transformer

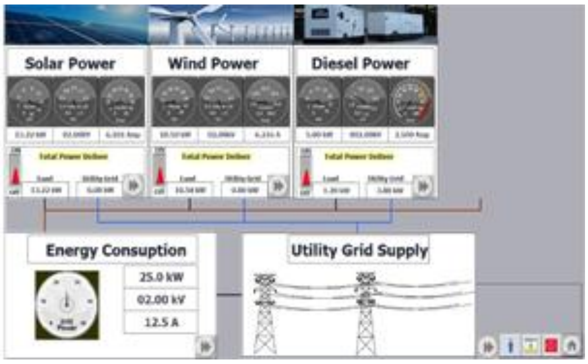

Fig. 6. Solar system SCADA

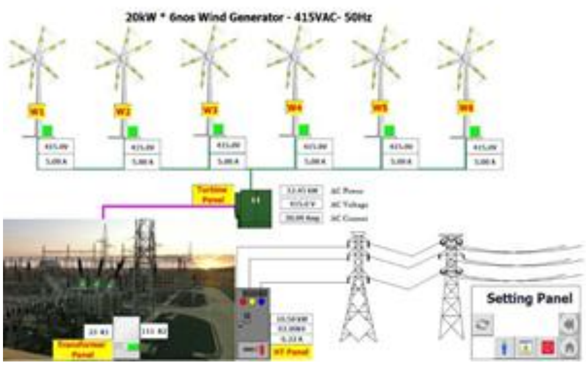

Fig. 7. Wind system SCADA

Fig. 8. Diesel system SCADA

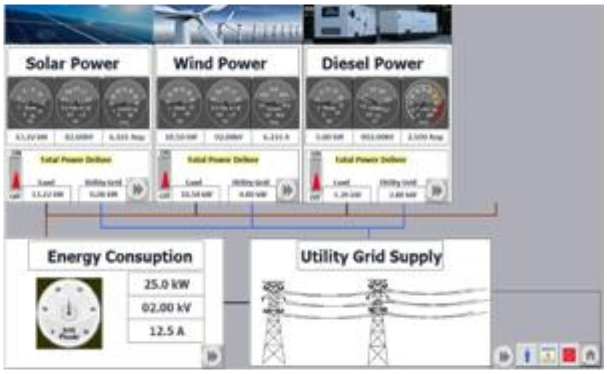

Fig. 9. Control system SCADA

The generated power deliver to the load and the control of the all structure is implemented by Programmable logic controller (PLC) as discussed earlier. Fig. (9) shows control system for SCADA implementation.

D. Simulation Results

The simulation results of voltage, frequency, active power sharing and reactive power sharing are shown in the Figs. (10) – (14)

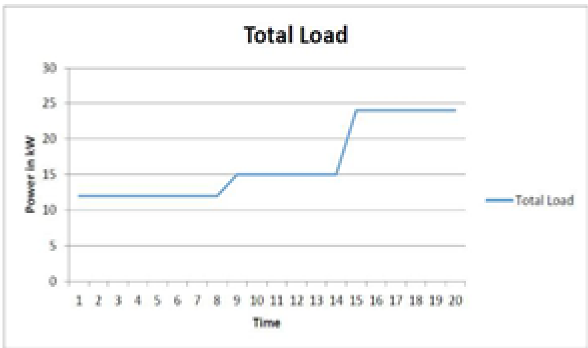

Fig. 10. Total Generation

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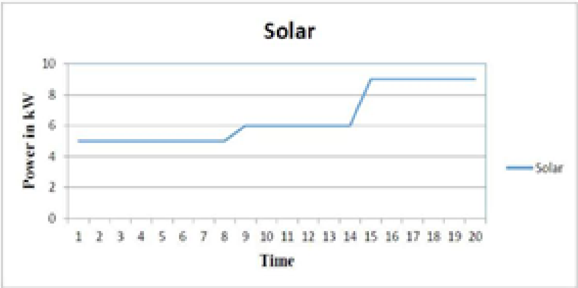

Fig. 11. Solar Generation

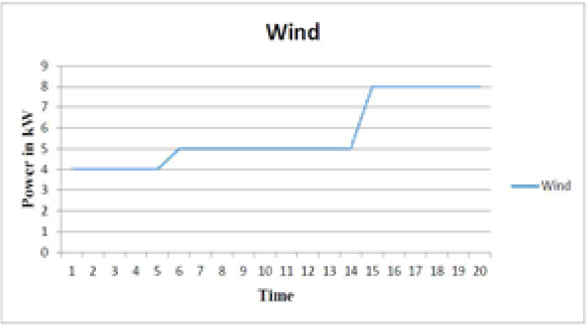

Fig. 12. Wind Generation

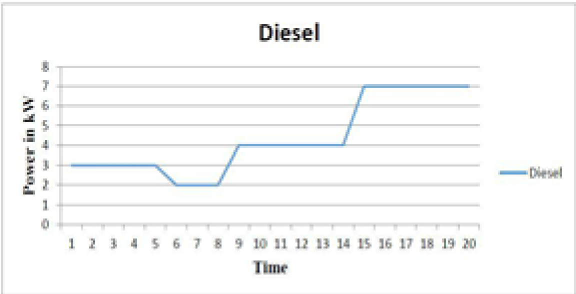

Fig. 13. Diesel Generation

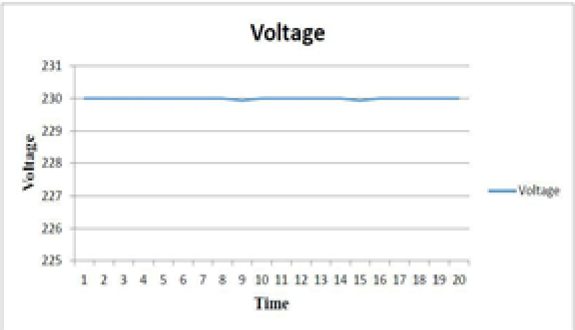

Fig. 14. System Voltage

6. CONCLUSION

In this paper distributed cooperative control of multi-agent system is implemented for the secondary voltage control of Microgrid using SCADA. Input-output feedback linearization is used to transform the nonlinear dynamics of DGs to linear dynamics. The controller for each DG is fully distributed and each DG requires its own information and the information of neighbors only for the secondary control. The distributed control structure overcomes the drawbacks of centralized and improves the reliability of the Microgrid secondary control and moreover each controller is independent of DG parameters and the connector specifications. The SCADA system provides reliable and efficient solution for Microgrid control system.

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