Real-Time Simulation of a Microgrid Control System using MODBUS Communication

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ABSTRACT

In recent years, microgrids have become increasingly common in power systems around the world. Microgrids have complex control and operational requirements, thus, a dedicated communication network is often a requisite for its functionality. Due to economic and logistical concerns, it is also desirable to keep the communication system as simple as possible. Among contemporary system automation protocols, the Modbus protocol is generally the simplest one to implement. This paper demonstrates the applicability of Modbus TCP communication in facilitating the control system of a detailed microgrid simulated in a real-time power system simulator. The simulated microgrid exchanges voltage, frequency, power measurements, breaker statuses as well as power set points of generators with a central control location via Modbus protocol, where a control system continuously monitors the microgrid. Control centre issues commands depending on the operating conditions of the microgrid such as to switch the microgrid controls from the grid connection mode to the islanded mode, change the protection relay settings groups and activate a load-shedding scheme. Implementation of relevant microgrid controls and Modbus communications are presented using an example microgrid case with the results obtained.

Keywords – Microgrids, Distributed Energy Resources (DER), Islanding, Modbus Communication, Hardware-In-the-Loop (HIL) Simulation, Real-Time Simulator

1. INTRODUCTION

A microgrid is a portion of a distribution network and is usually designed to operate in parallel with the power grid or autonomously as a power island [1]. In contrast to traditional distribution networks, a microgrid is generally a self-sustained entity with distributed energy resources (DERs) catering for its energy consumption. Integration of small-scale, renewable energy resources such as solar-PV, wind power and mini-hydro power is a key attribute of microgrids [2]. Modern microgrids are also equipped with energy storage devices such as battery banks. When properly managed, microgrids improve the overall power system performance in addition to providing significant economic and environmental benefits. However, safe and reliable operation of a microgrid in grid connected and islanded operation is a challenging task due to issues like islanding detection, protection coordination with bidirectional power flow, system stability concerns, and intermittent nature of renewable energy resources [3]-[6].

With their increasing popularity, safe, reliable and cost effective tools are necessary to study challenges in microgrid implementation, operation and control. Real-time hardware-in-the-loop (HIL) simulations are one of the best approaches in this regard, as the simulated system can replicate the actual microgrid system in detail [7], while allowing the interfacing of external device to the simulation. Real-time power system simulators can interface protection and control devices as well as power sources and communication equipment to a modelled microgrid. This enables systematical evaluation of performances of individual devices as well as the system as a whole.

The remainder of this paper is organized as follows. Section 2 explains the importance of a communication system in a microgrid. It further discusses why Modbus protocol is worth investigating as a suitable candidate for system automation in a microgrid. Section 3 provides information regarding the test microgrid system and its communication interface using Modbus protocol. In Section 4, test results are presented for several cases, where control actions are performed using the implemented Modbus communication interface. Section 5 follows with conclusions emphasizing the main findings of this paper.

2. INFORMATION EXCHANGE IN A MICROGID

Unlike conventional distribution systems, microgrids undergo frequent changes in operating conditions, enforced by energy sources as well as loads. Therefore, a microgrid has additional control and operational requirements than a conventional system, which demands real-time information exchange.

2.1. Requirement for a Dedicated Communication System in a Microgrid

As explained above, a microgrid must operate within acceptable limits in both grid connected and islanded modes. When switching to the islanded mode of operation, a microgrid should take appropriate control actions to maintain its local frequency. This usually involves changing the operation mode of one of its generators from droop control mode to isochronous frequency control mode, upon detection of the islanding [8], [9]. In addition, islanding often causes variations in power flow and voltage profiles within the microgrid. Changes to the microgrid topology may be required to remedy some of these issues. Furthermore, it is necessary to maintain power balance in the islanded mode by changing the reference power set points of DERs, connecting/disconnecting reactive power sources such as capacitor banks and enforce load shedding if load demand exceeds the available generation [3], [4].

In a power system protection perspective, islanding might cause complications to protection coordination of the system [5], [6]. In general, fault levels in a microgrid are lower in islanded mode than they are in grid-connected mode, as the fault current contributions from the main grid are now absent. Fault levels become further unpredictable due to the intermittent nature of renewable type DERs, which are often an integral part of modern microgrids [10]. Moreover, DERs, particularly those with full-frequency converters such as solar-PV and type-4 wind generation, pose unique challenges to power system protection [11]. These complicated operating conditions demand protection relays to vary their protection settings and configurations, depending on circumstances.

Operation of modern microgrids are also affected by economic considerations, which demand available energy resources to be dispatched optimally, without violating system operating limits [12]. This generally involves harnessing the maximum amount of power available from renewable type DERs. The intermittent nature of the power output from these type of sources essentially means that the power set points of other generation must be varied dynamically.

It is the role of the microgrid control system to manage all of the above-mentioned control and protection considerations. A microgrid control system can be implemented as a central unit or a distributed system, but both architectures require a microgrid to have a dedicated communication network. In addition, monitoring and supervision of system data is an integral part of the control system as well.

2.2. Automation of Microgrid Communication

There are a number of existing protocols suitable for automation of information exchange in a microgrid such as IEC 61850, DNP3, IEC 60870-5-104 and Modbus [13]. Although less refined than its newer counterparts, Modbus protocol is often the simplest and the least expensive option among them. When configuring a comparatively smaller system such as a microgrid, using Modbus can be more convenient to use than a protocol like IEC 61850. However, IEC 61850, with object oriented data modelling and a rigorous engineering process, has distinct advantages when the system under consideration is large [14]. Low bandwidth requirements of Modbus is also ideal for a microgrid, where laying out a complex communication network is often not feasible. Moreover, Modbus protocol provides sufficient interoperability and robustness and, remains a commonly supported protocol by relays and other intelligent electronic devices (IEDs).

Modbus is a protocol with a client/server architecture, originally designed with serial communication for system automation to facilitate communication between a master station and a Remote Terminal Unit (RTU) [15]. A Modbus master (the client) interfaces with one or multiple slave stations (the server) using a request/reply routine. In general, a Modbus transaction is always initiated by the master and the slaves transmit data only as a reply. Currently, Modbus protocol has few implementation variants and supports both serial and internet protocol (IP) communication [16]. In this paper, Modbus TCP protocol is proposed for data communication and automation of a microgrid control system.

3. MICROGRID CASE AND TEST SETUP

The test system used in this paper is a modified version of CIGRE C6.04.02 benchmark North American medium voltage distribution network [17]. The topology of the microgrid structure is shown in Fig. 1.

Table I Information exchanged between Modbus slaves at each location and the master at control centre

Location	**Input/output Data Points**			
	Monitoring (read only)		**Control (read-write)**	
	Discrete Inputs	**Input Registers**	**Coils**	**Holding registers**
Bus 1 (B_1)	S_1 status S_{cap} status L_1 status	Current through S_1 B_1 voltage B_1 frequency	S_1 S_{cap} (1 to 3) R_2 activation	
Bus 2 (B_2)	L_2 status BRK_{26} status	B_2 voltage B_2 frequency	BRK_{26} R_1 Setting group R_3 activation	
Bus 3 (B_3)	L_3 status S_3 status BRK_{PV} status	B_3 voltage B_3 frequency PV power output	S_3 BRK_{PV} R_4 activation	
Bus 4 (B_4) and Bus 5 (B_5)	L_4, L_5 status S_2 status BRK_{Wind} status	B_4 voltage B_4 frequency Wind power output	S_2 BRK_{Wind} R_5 activation	
Bus 6 (B_6)	L_6 status	B_6 voltage B_6 frequency		
Bus 7 (B_7)	L_7 status BRK_{Die} status	B_7 voltage B_7 frequency DG power output	BRK_{Die} DG Mode Control	DG Power set-point

The microgrid is connected to a 138 kV main grid through a 25 MVA, 138/13.2 kV Δ-Y transformer with 8% leakage impedance [18]. There are three DERs in the microgrid including a 1.74 MW PV system connected to bus B_3 and a 2.0 MW doubly-fed induction generator (DFIG) wind turbine system connected to bus B_5. In addition, a 5.5 MVA diesel generator is connected to bus B7. A switched capacitors bank rated at 500 kvar is connected at bus B_1 to provide reactive power support. The microgrid is interconnected using a circuit breaker S_1. Circuit breakers S_2 and S_3 are kept open to maintain a radial network in grid connected mode. S_2 will be closed following an islanding to increase the system reliability. The total active and reactive loading of the microgrid are 7.39 MW and 2.936 Mvar, respectively [18].

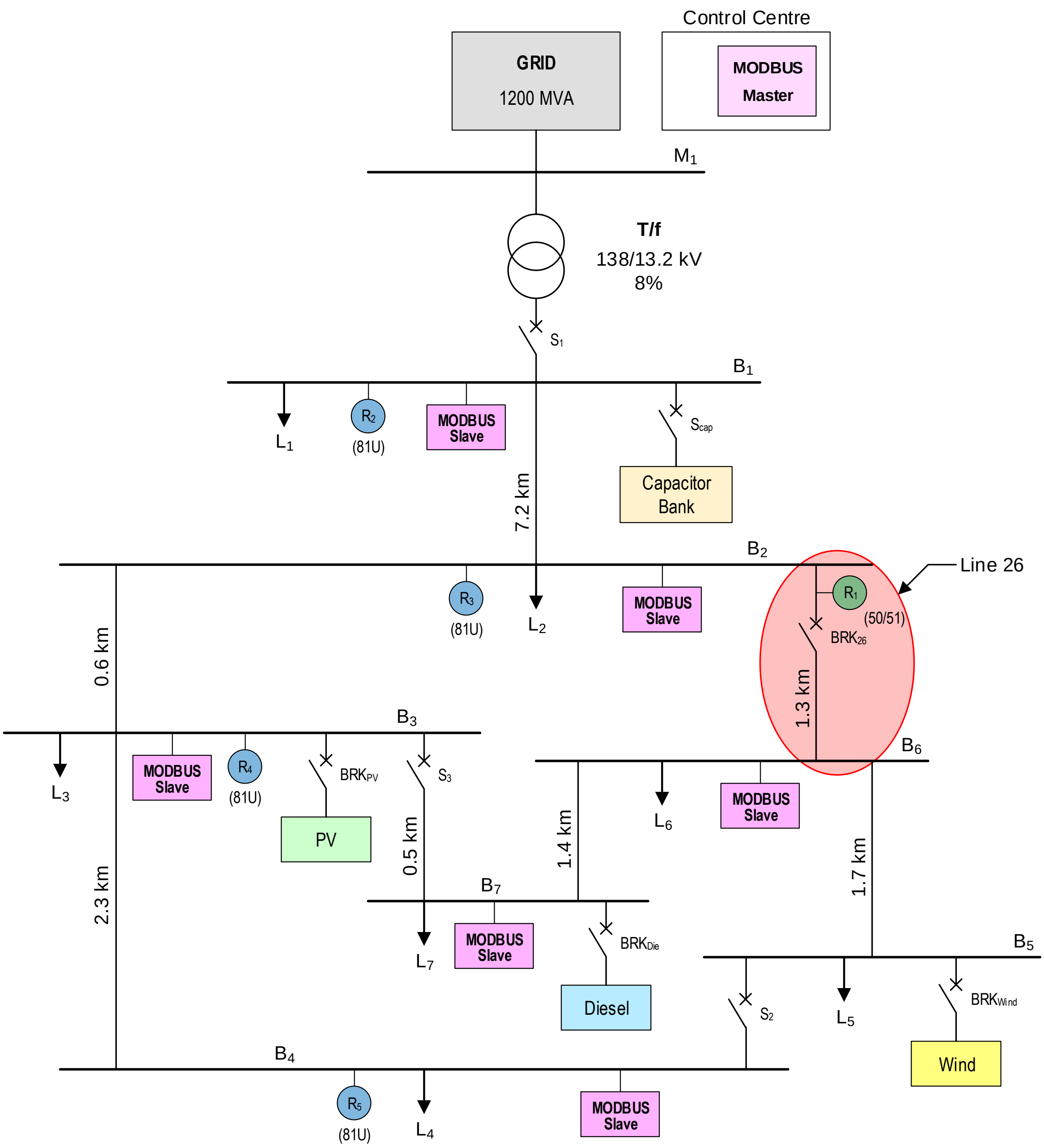


Fig. 1 Topology of the Microgrid with MODBUS Slaves

It is assumed that each bus shown in the microgrid has a Modbus slave capable of responding to requests sent by the Modbus master at the central control centre. Locations of the Modbus communication devices are also shown in Fig. 1. Information exchanged between Modbus slaves and the master at the control centre are provided in Table I.

In an actual microgrid system, each of the six locations as illustrated in Fig. 1 must have Modbus slave devices in order to complete the microgrid communication system. In this real-time simulation setup, one Modbus slave is sufficient to interface with the remote Modbus master as all the data points are internally generated and therefore, available inside the simulation itself. The Modbus slave interface in the real-time simulator has the capability to accommodate hundreds of data points of each type [19]. If required, however, this test setup can be modified without difficulty to accommodate independent slaves by adding multiple network interfaces cards.

A schematic of main connections of the microgrid test setup is shown in Fig. 2. The microgrid given in in Fig. 1 and all its controls are modelled inside the main simulation. The main simulation uses an electromagnetic transient type solution algorithm and runs on a dedicated hardware platform in real-time. Data generated inside the simulation are mapped to the Modbus slave using an internal points mapping file attached to the Modbus component in the simulation. Combination of the Modbus component and the network interfaces card of the simulator works as a Modbus slave, and any properly configured Modbus master can connect to it. All communications are carried out using Modbus TCP protocol.

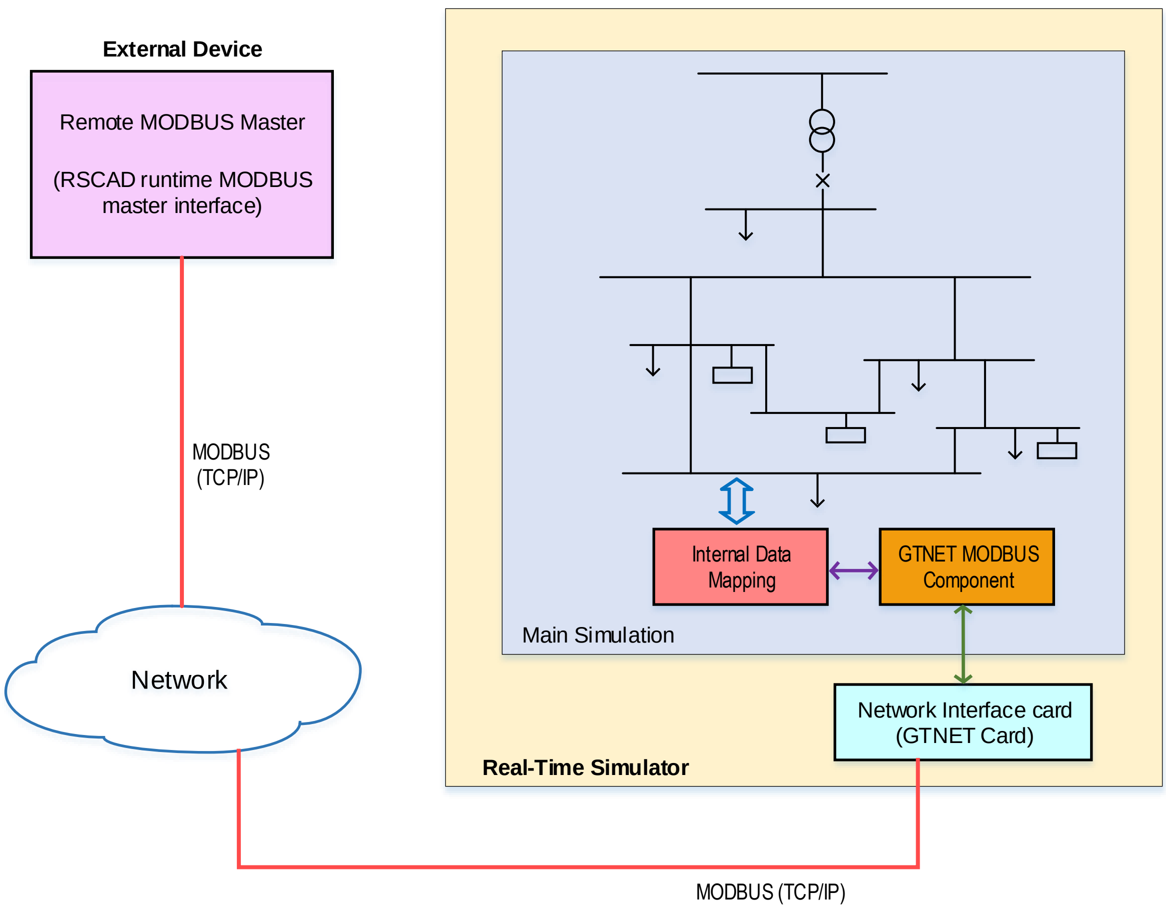


Fig. 2 Connection Setup between Devices

Runtime scripting feature of the real-time simulator supports Modbus master commands, enabling implementation of the Modbus master interface for the microgrid control centre in the workstation computer that runs the simulation. As depicted in Fig. 2, the remote Modbus master resides external to the real-time simulator in the workstation computer and implemented using a runtime script file.

4. Test Results

The Modbus master is continuously requesting measurements and statuses values from the slaves as indicated in Table I. In turn, the control centre issues appropriate commands, when changes in operating conditions of the microgrid are detected. The following sub-sections present few such scenarios with the results obtained.

4.1. Islanding Detection

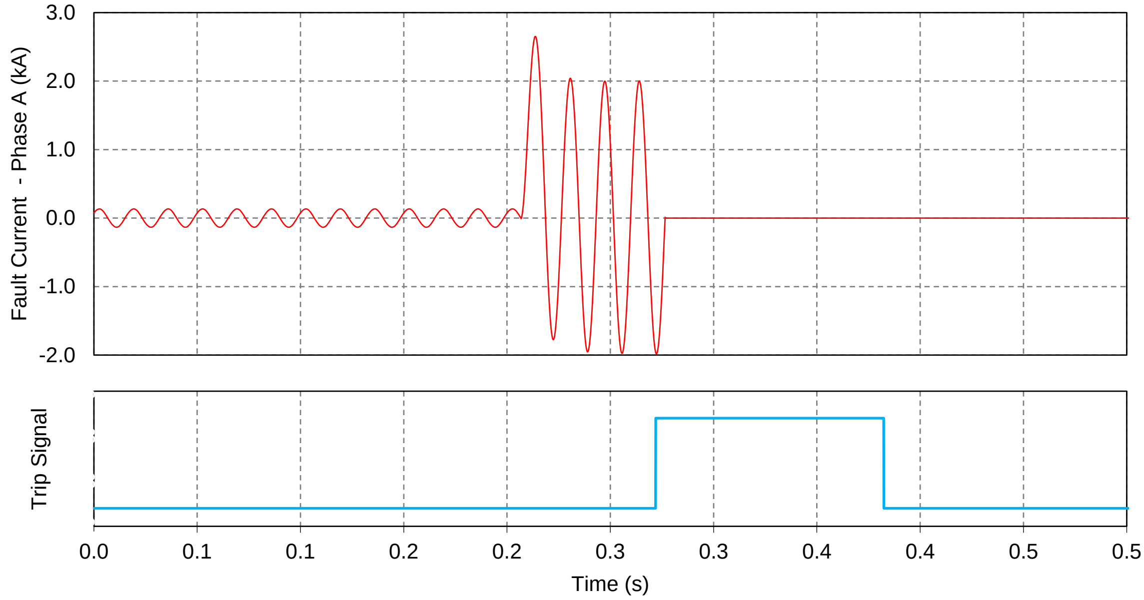
In this microgrid test setup, an islanding event is detected based on the status of the circuit breaker at the point of common coupling, S_1. The microgrid control system continuously monitors the status of the S_1 circuit breaker via Modbus. When the control system detects the opening of S_1, it issues a Modbus command to the diesel generator to switch into isochronous frequency control mode from droop control. The diesel generator is then responsible for maintaining the local frequency while the microgrid is in the islanded mode. Similarly, the control system commands the diesel generator to switch back to droop control mode, once after the microgrid has reconnected to the main grid.

4.2. Switching Relay Setting Groups

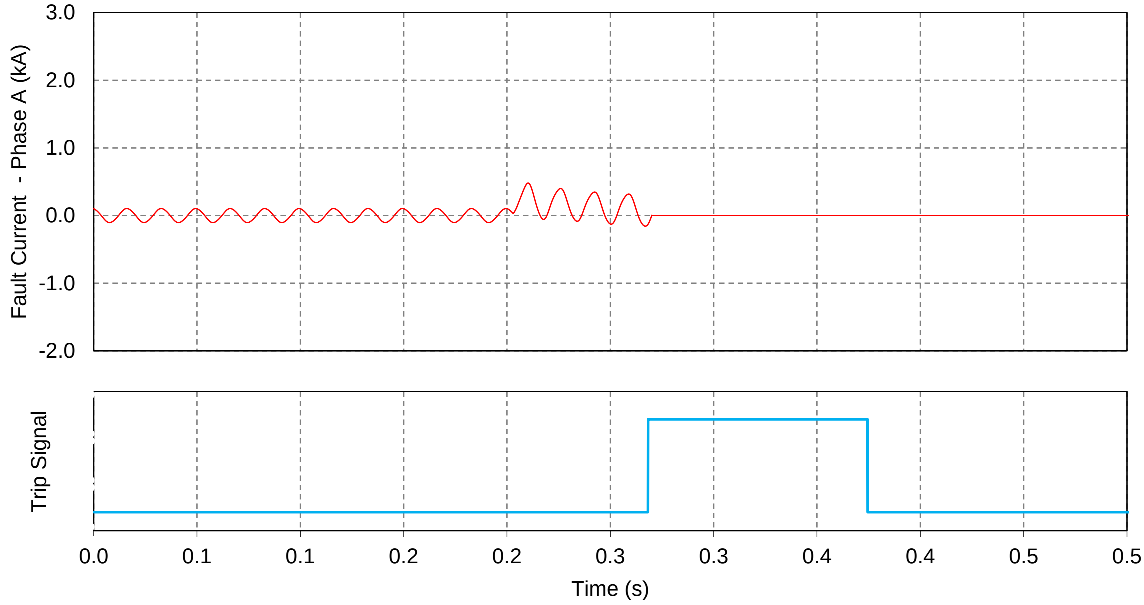
As explained in Section 2, islanding of the microgrid causes changes in the system that demands adjustments in protection settings. One such case is presented in this sub-section with results.

In grid connected mode (and with both S_2 and S_3 open), phase A current of Line26 measured at bus B_2 is around 93 A (in this case, the load currents are unbalanced). During an A to ground fault on bus B_6, phase A of Line 26 will observe a steady state fault current around 1400 A at bus B_2. In contrast, when the microgrid has islanded, the same line would carry a load current of 75 A and observe a steady state fault current of only 171 A. The marked decrease of fault current magnitude in the islanded mode is understandable due to the absence of the fault current contributions from the main grid. Here, the fault is mainly fed by a solar PV system, which is known to produce weak fault current contributions [11]. Overcurrent protection is often the preferred protection method used in distribution level, including microgrids and in order to counter such a variation in fault levels, different relay settings are necessary [20]. The most convenient way to accommodate this is to have two settings groups in the relay and switch between them depending on the microgrid operation mode.

In order to demonstrate this phenomenon, overcurrent protection is applied to Line26 as indicated in Fig. 1. Here, the relay R_1 at bus B_2 carries two setting groups and assumed to have Modbus slave capabilities. The control centre commands the relay to switch between setting groups using Modbus communication. Fig. 3 below presents the fault currents and the corresponding trip signals from the relay R_1, for an A-G fault at bus B_6. One can observe the variation of fault currents from grid connected mode to islanded mode. Accurate settings allow prompt operation of relays, enabling the microgrid to return to its stable operation following a fault, without enforcing load shedding.



(a) Grid Connected Mode



(b) Islanded Mode

Fig. 3 Fault Currents and Trip Signals

4.3. Adjusting the Power Reference of the Diesel Generator

Economics involved with energy production demand that irrespective of the mode of operation of the microgrid, both the solar PV system and the wind plant harness the maximum available amount of energy from their respective sources. In islanded mode, the diesel generator must cater for the rest of the load by its own, while maintaining the load-generation balance of the microgrid (and consequently, the frequency as well). In grid-connected mode, however, the diesel generator is operating on a droop with a specified active power reference. This allows the diesel generator to adjust its power output in an optimal manner. In this study, active power imported from the main grid is kept constant at a low value when possible, with the idea of keeping the microgrid a self-sustaining system.

Plots shown in Fig. 4 illustrates how the microgrid control centre adjust the active power reference set point of the diesel generator, upon detecting an increase of the wind power output. The controller constantly monitors the power outputs of the wind and solar systems and adjusts the power reference set point of the diesel generator accordingly. In Fig. 4, it can be seen that as the power output of the wind plant increases, there is a temporary decrease of the active power imported from the grid until the diesel generator settles at its new power reference set point. A similar behavior can be observed when the power output of the wind plant decreases. In addition, there is no discernable change in either the voltage magnitude or the frequency at the point of common coupling due to this control action.

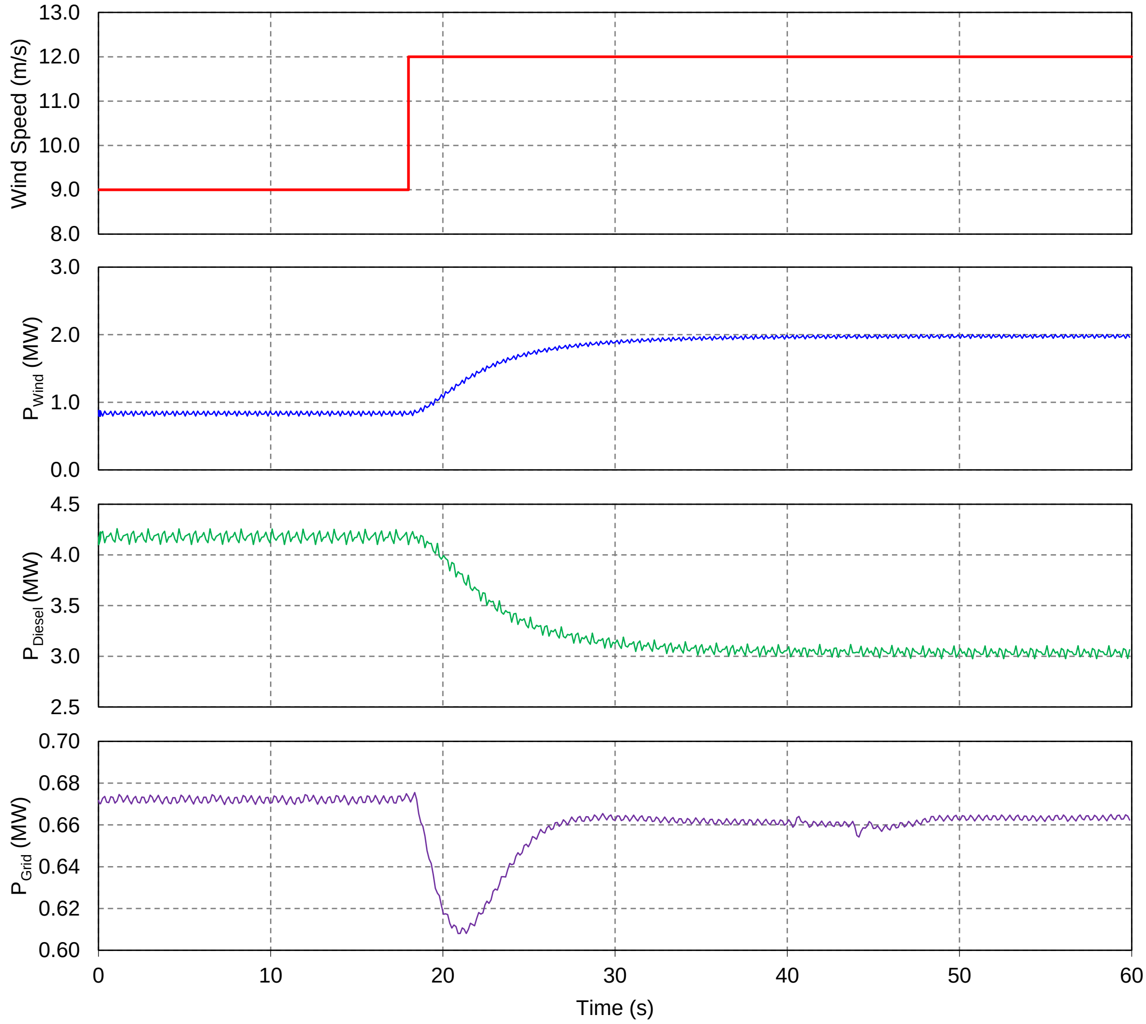


Fig. 4 Responses of Wind Output, Diesel Output and Power Imported to the Microgrid with Wind Speed Variation

4.4. Load shedding scheme

An under frequency load shedding scheme is implemented in this microgrid system to arrest a significant drop in system frequency. Its function is vitally important to maintain the load-generation balance when the microgrid has islanded. The microgrid control centre enables the under frequency function at different locations of the microgrid using Modbus commands, following an islanding. In this setup, loads connected to buses B_1, B_2, B_3 and B_4 are presumed to be non-critical and will be dispensed with by the load-shedding scheme in an emergency. The loads are shed by under frequency relays at respective buses in response to local frequency measurements. The relays' algorithm has pickup thresholds for both under frequency and rate of change of frequency. In Fig. 5, the operation of the load-shedding scheme is provided for a sudden decrease of wind power output. In this case, microgrid frequency recovered back to the nominal range by disconnecting L_1 and L_2 only (loads connected at buses 1 and 2, respectively).

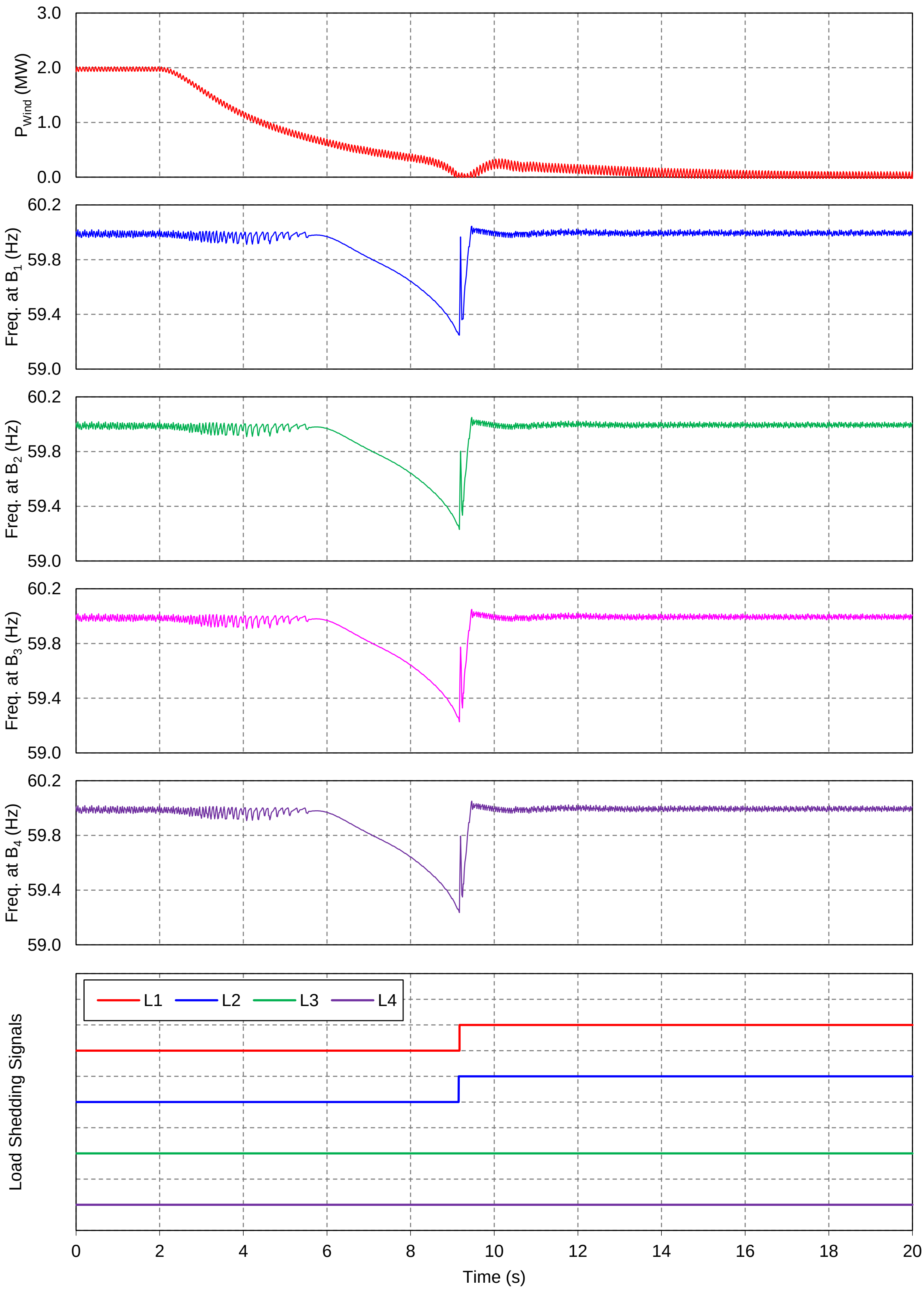


Fig. 5 Operation of the Load-Shedding Scheme due to a Frequency Drop caused by a Loss of Wind Power Output

5. CONCLUSIONS

This paper has presented the use of the Modbus TCP protocol for operational and control applications of a microgrid. Several microgrid control actions were performed on a detailed microgrid model simulated in an EMT type real-time simulator. All information was exchanged using real Modbus TCP communication between a Modbus master and a slave. Results presented in this paper substantiates that Modbus TCP protocol is well suited for carrying out communication requirements of a smaller system like a microgrid. Furthermore, the results indicate that when implemented on modern hardware platforms, Modbus TCP protocol is responsive enough to execute fast and complex control operations such as dynamically changing the power reference of a generator.

In addition, this paper demonstrates the necessity of a dedicated communication system for modern microgrid systems with complex operational and control requirements. This paper further highlights the advantages of using a real-time simulator for microgrid studies, where the users can not only model the system in detail, but also interface external protection and control devices using real communication.

6. REFERENCES

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