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Relay coordination analysis and protection solutions for smart grid distribution systems

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Abstract: Growing complexity of conventional power grids and their management, increasing power demand and energy quality expectations considering grid reliability, and efficiency and security concerns have triggered the evolution of smart grids. This is an expected result of implementing new technologies in existing grids, including renewable sources such as wind turbines and photovoltaic modules. With implementation of such new elements to the system, the protection concept should be considered by system regulators. In order to analyze protection problems, simulation-based analysis should be carried out before high-cost experimental studies. In this study, a simulation-based evaluation for a smart grid-based distribution system is performed. System simulations are realized considering different fault cases and optimum operating conditions are obtained. A ring grid is designed including a generator and a wind turbine as sources and variable loads as consumers. Several points in the grid are selected as fault locations, and the condition of connecting distributed generation plants to the grid is evaluated in the MATLAB/Simulink environment. This study presents an analysis about the possibility of forming a grid with high reliability and efficiency under fault conditions.

Key words: Relay coordination, smart grid, overcurrent protection, short-circuit protection

1. Introduction

In response to increasing energy demand, new substations and consumers are added to existing grids. Equipping conventional grids with today's computer and network technology provides the basis of a new generation of grid structure within the definition of "smart grid", which aims to achieve a reliable and sustainable energy supply [1]. Existing grid structures have significant drawbacks, such as manual fault detection, independent voltage regulation, nonoptimized power flow, and limited power management. Besides, such conventional grid infrastructures are extremely dependent on each other. Hence, a fault or any other undesirable event that occurs in any location of the grid can rapidly affect a huge part of the system and this problem may cause more damage to the total grid [2]. In order to solve this problem, the disadvantages of grids must be eliminated and improved grid solutions must be implemented [3].

Smart grids offer some technological developments to improve the grid, such as real-time fault detection, remote switching, real-time power management, and dynamic simulations for minimizing losses. With the purpose of detecting possible faults and finding rapid solutions, a reliable communication system is needed, which is available in the smart grid concept to support the data acquisition, protection, and automatic control of the smart distribution grid [4]. The mentioned communication system should be operated in a reliable and efficient way to maximize productivity, reliability, and efficiency of the system [5].

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Another important benefit of smart grids is the effective selectivity issue that is significantly important at the time of fault events in system protection. It will be possible to prevent extension of faults to large areas of a grid with a short response time. This can be achieved by fast protection and remote control systems [6]. Through the advanced measurement, protection, and communication features of smart grid structures, automatic fault detection and insulation can be performed easily [7]. An automated power restoration algorithm is the most recent advancement to have a fully automated application [8]. There are several options to define the selectivity concept in order to ensure continuous supply of energy to customers once the location of the fault is detected [9]. After isolating the fault location from the grid by using breakers, the consumers that are not fed will be powered by other sources in the grid. In order to facilitate such a performance, conventional grids have to be equipped with necessary communication and protection tools and should be upgraded to smart grids.

In this paper, a modified version of the IEEE 13-node test system is used to ensure effective selectivity after a fault event considering the concept of smart grids [10]. The evaluated smart grid structure includes several types of energy producers (conventional generators, distributed sources, etc.) and consumers. After a fault event occurs in the proposed test system, only the fault location is separated from the grid. Signals from protection relays are sent to open the related circuit breakers without shutting down the energy of the whole system. One of the major challenges in designing a smart grid is the implementation of distributed generation (DG) units, which change the protection concept due to the two-way power flow. Thus, the case of connecting DG plants to the grid is realized and related analyses are performed in this study. A wind turbine (WT) is chosen as a DG unit and included in the IEEE 13-node test system. Different overcurrent and short-circuit protection methods are applied to the feeder of the WT in order to prevent undesired operation of breakers. The simulation-based analyses are performed in the MATLAB/Simulink environment. Relay controls of the power system are realized by employing proposed supervisory control methodologies. The proposed method is capable of effectively detecting the fault, isolating fault locations from the grid, and feeding consumers from another possible line until the fault is cleared. First, system simulations are realized for fault analysis, and then optimum operating conditions of the grid are presented and the results are discussed. The main contribution of this paper will be relay coordination between the conventional grids and DG plants, which has an important role in protection.

The rest of the paper is organized as follows: Section 2 includes system methodology and simulations. In Section 3, the results obtained from simulations are given and the system behaviors during the faults and after fault clearance are discussed. Finally, the general concluding remarks are presented in Section 4.

2. System methodology and simulations

The general scheme of the modified version of the IEEE 13-node test system is shown in Figure 1, which includes control, communication, and power system components. It is to be noted that the test grid is supplied by a generator and a WT. Consumer loads are modeled by inductive and capacitive impedances.

Relay and breaker models are used in simulation in order to realize protection (Figure 1). In designing the relay model, the standard inverse characteristic (SI) is used [11]. Operating time characteristics of the relay model are given below in Eq. (1):

$$t_{si} = \frac{0.14}{[I^{0.02} - 1]}\ s. \tag{1}$$

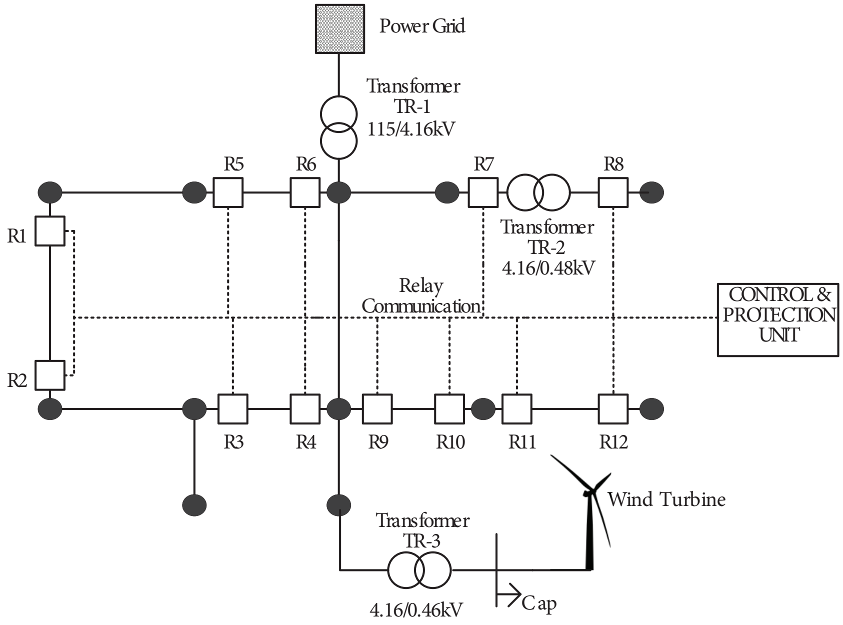

Figure 1. General system configuration.

It is essential to clear any fault event as fast as possible [12]. After detecting the fault location, the solution should be chosen according to the selectivity procedure to ensure that the circuit breakers operate in a rapid and reliable way.

During a possible fault, only related areas should be isolated from the grid by controlling the breakers. That means the ring grid's supply system will be changed after the isolation of the fault area. The consumers are fed by a generator and WT via transformers as mentioned above.

The voltage level of the generator is the same as the voltage level of the WT under normal operating conditions. The aim of a supervisory controller is to keep the voltage level stable during a fault event.

In order to test the reliability of the system, some fault events are applied to different locations in the test system to evaluate the effectiveness of the proposed controller. The maximum value of short-circuit currents is predicted to be occurring at the output of transformers [13]. The breakers used in this simulation are controlled by external signals received from the supervisory controller. The control signals of breakers are dynamically changed under different conditions. Input signal of breakers is defined as "closed" and "open". The "closed" signal is sent to breakers if energy of the system is desired and "open" is sent to breakers if it is aimed to isolate a fault location from the rest of the grid [14]. The flow chart of the mentioned control algorithm is shown in Figure 2. While output signal of the algorithm commands the breakers, the input signal of the algorithm is measured from current transformers located on the distribution line. After the desired signal is received from the algorithm, output signals are defined as initial conditions by employing a time delay action.

3. Test and results

Case studies are applied to the IEEE 13-node test system and simulation results are obtained by MATLAB/Simulink and SimPowerSystems.

The necessary details of the simulations are presented in this section. The WT connected to the distribution grid includes a mechanical WT model and an asynchronous generator. The wind speed for generating nominal power from the WT should be 12 m/s. However, the wind speed is not constant during operating conditions. For that reason, an average of 10 m/s wind speed is selected and applied to the WT model. The WT power characteristics are given in Figure 3. The asynchronous generator power data include 37.3 kVA nominal power, 460 V voltage (line–line), and 60 Hz frequency. The WT data include 1.5 MW nominal mechanical output power and 1.5/0.9 MW base power of the electrical generator.

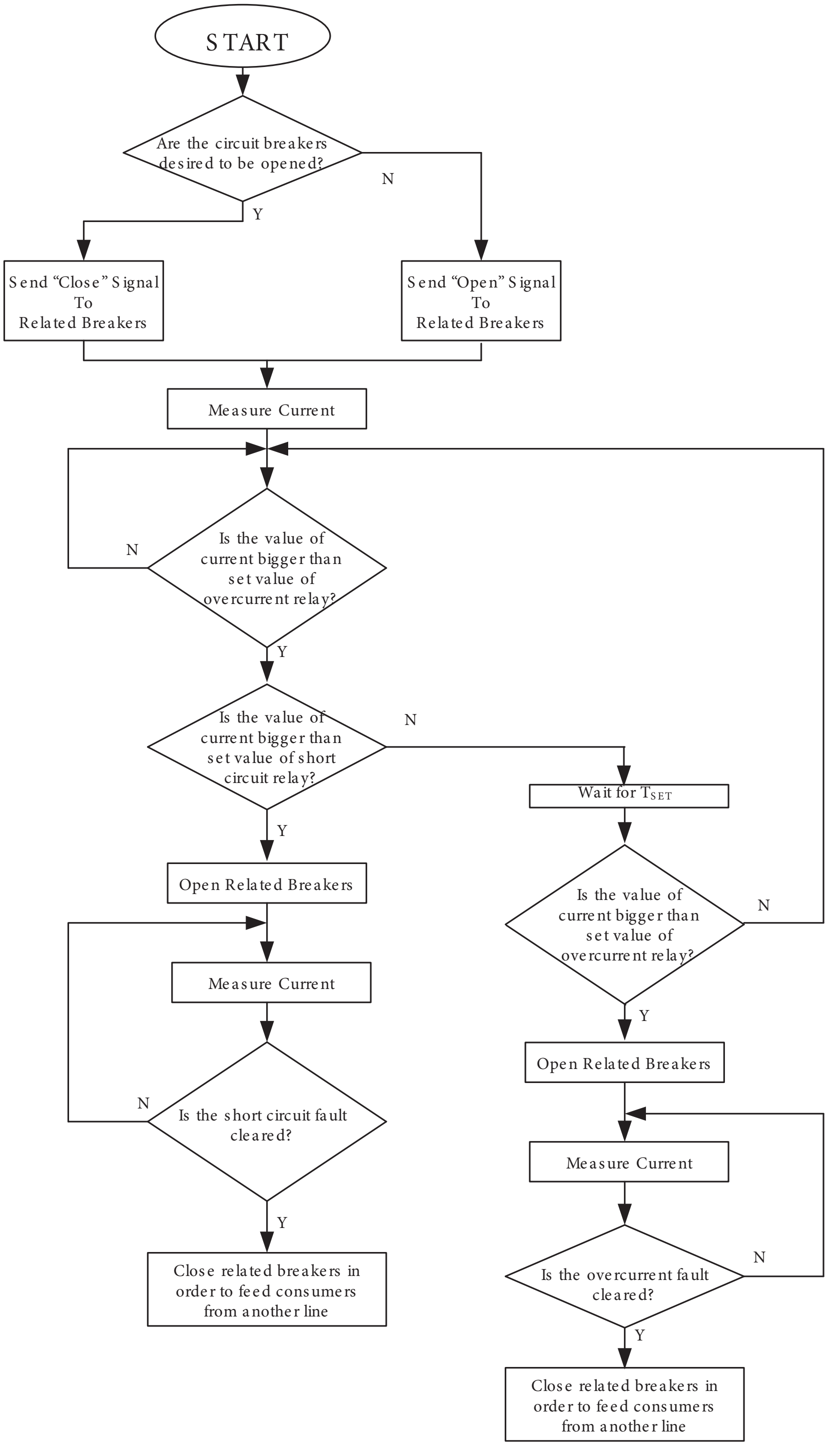

Figure 2. Control algorithm.

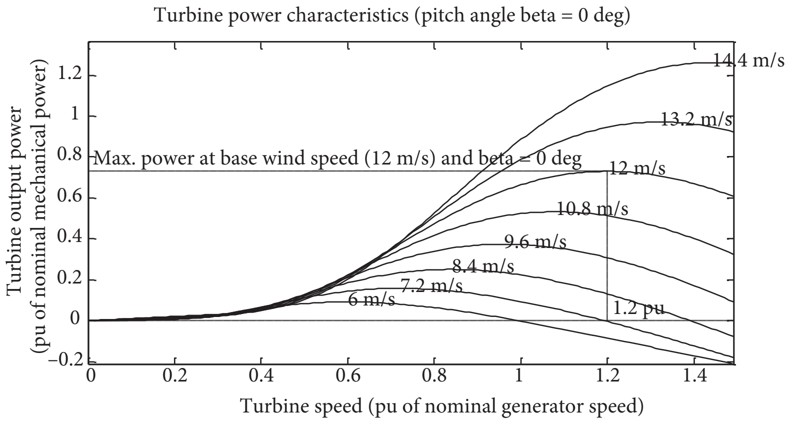

Figure 3. WT power characteristics.

The instantaneous load and line segment data of the employed IEEE 13-node test system are listed in Table 1. In addition, IEEE 13-node test system transformer data are given in Table 2.

Table 1. Instantaneous load and line segment data.

Spot loads								Line segment data			
Node	Load	Ph - 1	Ph - 1	Ph - 2	Ph - 2	Ph - 3	Ph - 3	Node A	Node B	Length(ft.)	Config.
	Model	kW	kVAr	kW	kVAr	kW	kVAr	632	645	500	603
634	Y - PQ	160	110	120	90	120	90	632	633	500	602
645	Y - PQ	0	0	170	125	0	0	633	634	0	XFM-1
646	D - Z	0	0	230	132	0	0	645	646	300	603
652	Y - Z	128	86	0	0	0	0	650	632	2000	601
671	D - PQ	385	220	385	220	385	220	684	652	800	607
675	Y - PQ	485	190	68	60	290	212	632	671	2000	601
692	D - I	0	0	0	0	170	151	671	684	300	604
611	Y - I	0	0	0	0	170	80	671	680	1000	601
	Total	1158	606	973	627	1135	753	671	692	0	Switch
								684	611	300	605
								692	675	500	606

Table 2. Transformer data.

Transformer data					
	kVA	kV - high	kV - low	R - %	X - %
Substation	5.000	115 - D	4.16 Gr. Y	1	8
XFM - 1	500	4.16 - Gr.W	0.48 - Gr.W	1.1	2

The system is designed and modified with two new lines in order to realize the smart grid structure. The new lines are implemented for ensuring continuity of energy during fault events.

The system is connected to a power grid that has a voltage level of 115 kV from node 650 through a transformer rated 115 kV/4.16 kV. The WT also generates 460 V voltage and transfers it to 4.16 kV through a transformer. Fault blocks used in the test system are applied to two different locations, at the output of transformer and a long distance from the transformer, to simulate maximum and minimum levels of fault events.

Three different scenarios are applied to the IEEE 13-node test system in order to verify the reliability of the proposed protection system. The first scenario (Scenario 1) includes a short-circuit event occurring in the grid structure. In this scenario, three phase to ground short-circuit fault is simulated. The mentioned scenario is shown in Figure 4.

In Scenario 1, the short-circuit fault is applied to line B, which is between node 645 and node 632, at 0.8 s. After a short-circuit fault, the protection system must operate quickly in order to protect other parts of the grid. In normal conditions, line C does not operate and lines A, B, and D feed the consumers. During the fault event, consumers in line A will not be fed in normal conditions after line B is isolated from grid. However, the consumers in line A can be fed through line C with the help of the designed smart grid protection system. Line A currents in normal operation and after fault clearance are given in Figure 5.

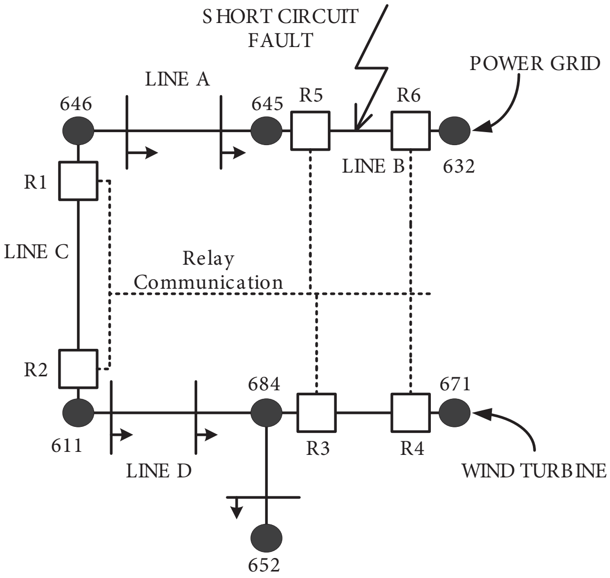

Figure 4. General scheme of first scenario.

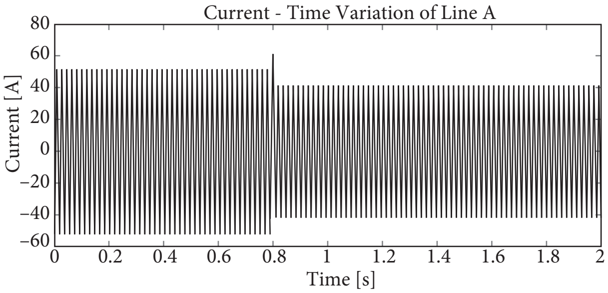

Figure 5. Current waveform of line A during first scenario.

Figure 5 shows that the protection system enables consumers on line A to be fed. In normal conditions, the protection system shows the current wave form of consumers located in line A. After fault event and isolation of line B, the ampere-meter indicates the current wave form of consumers located in line A. This result shows that the consumers on line A are not effected by energy interruption. Consumers of line A will be fed through line C after a fault event and isolation of line B.

Figure 6 shows isolation of line B after a short-circuit fault. Current value for line B is 100 A before short circuit and the current reaches 750 A at the time of the fault, which is an undesired situation. Because of this issue, the protection system sends an “open” signal to related breakers and isolates the fault location from the grid.

Current waveform at the output of transformer 1 is shown in Figure 7. The effect of short circuit can be seen as a current peak value at 0.8 s. The protection system enables the grid to continue operating. After the fault event, the system is fully operating thanks to the applied protection methods.

Scenario 2 includes an overcurrent situation in the grid. In Scenario 2, a new methodology for the protection system has been designed and applied to the system for overcurrent faults. Figure 8 indicates the location of the fault and system configuration for Scenario 2.

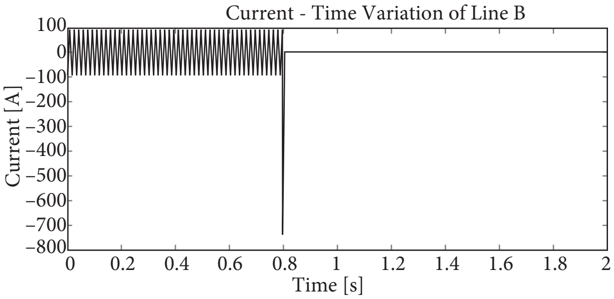

Figure 6. Current waveform of line B during first scenario.

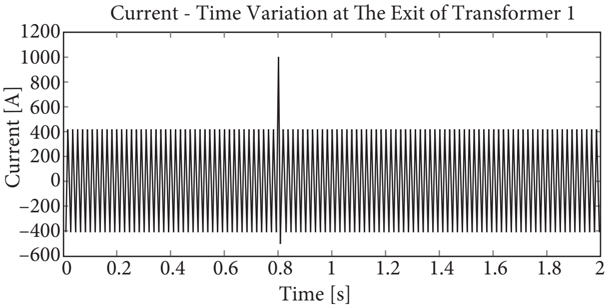

Figure 7. Current waveform at the output of transformer 1 during first scenario.

The overcurrent protection method in Scenario 2 has some differences from the short circuit protection method employed in Scenario 1. First of all, the overcurrent protection system is equipped with additional protection methods in order to realize time delay. If the current value of the line is greater than a set value of current, an open signal is not directly sent to breakers. Time delay blocks, which are designed for realizing the 735/737 ANSI normal inverse curve, receive a signal from function blocks during fault and transmit them to breakers with the relevant delay time. Figure 9 indicates system configuration of the mentioned overcurrent relay model.

Figure 10 indicates an overcurrent situation occurring in the grid at 0.8 s. If the duration of overcurrent is longer than the set time value, the protection system sends an “open” signal to the related breakers. As seen in Figure 10, duration of overcurrent is longer than the set time value and an open signal is sent to the circuit breakers. In Scenario 2, a shorter overcurrent period is tested as another case. Obtained results indicate that the system operates quickly in order to actualize protection for variable fault periods.

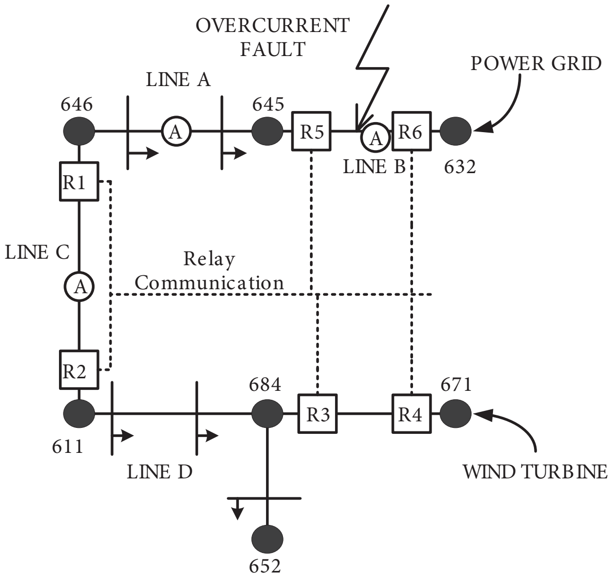

Figure 8. Overcurrent protection test system configuration belonging to second scenario.

In Scenario 3, a shorter overcurrent period is analyzed. If duration of the overcurrent is shorter than the set time value, the system does not send an “open” signal to breakers. The time delay function counts to the set value of time. Figure 11 indicates the related condition of short overcurrent time.

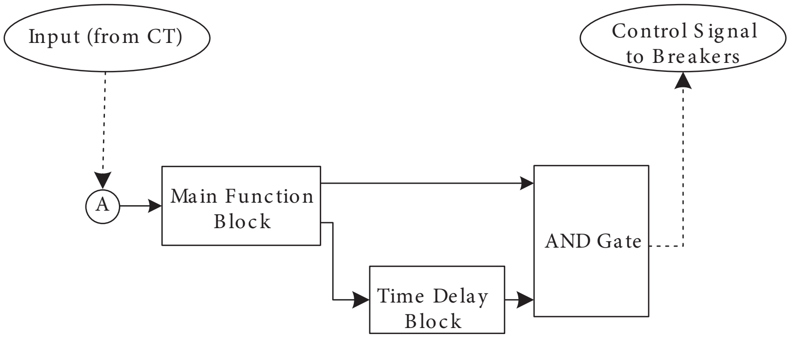

Figure 9. Overcurrent relay configuration.

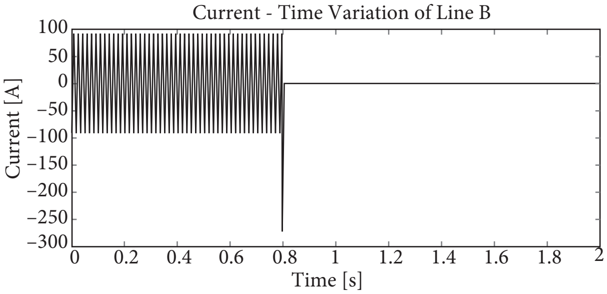

Figure 10. Current waveform of line B during second scenario.

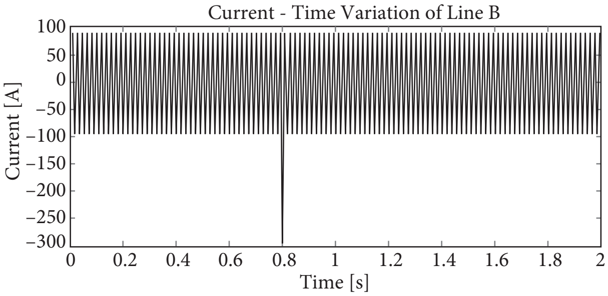

Figure 11. Current waveform of line B during third scenario.

Figure 11 shows that if the duration of overcurrent fault is shorter than the set time value, the protection system does not send an "open" signal to related breakers. After an overcurrent event occurs at 0.8 s, the system continues to transmit power immediately, as seen in Figure 11.

The above given results for three different scenarios indicate that the protection system operates satisfactorily. Scenarios for overcurrent and short-circuit faults are realized and possible fault conditions for the distribution grid are tested. Thus, it is ensured that the protection system realizes continuity of energy during overcurrent and short-circuit events.

It can shortly be stated that the proposed control approach can be used to realize the continuity of energy. The mentioned control approach enables the system to operate continuously during any possible fault event.

4. Conclusions

The IEEE 13-node test system is modeled and modified by employing 2 new lines to implement smart grid operating conditions. The system also includes a WT through a transformer and circuit breakers. Smart grid protection methods are applied to the proposed system in order to protect the grid from overcurrent and short-circuit faults. During a possible short-circuit and overcurrent event in the grid, breakers effectively isolate the fault location and ensure the consumer's load supply through another line.

Simulation results indicate that the system operates satisfactorily. In a short-circuit event, the protection system responded quickly to open the related circuit breakers. In an overcurrent event, the protection system evaluated the duration of fault and produced two different responses for different scenarios. The mentioned responses for applied scenarios are opening circuit breakers and feeding the consumers from another line for a long overcurrent period and to keep consumers fed through the same lines for a short overcurrent period. The WT generates variable power values by the effect of wind speed. In order to keep the power level stabilized and realize protection of the WT, a control algorithm is implied to the system. The issue of integrating WTs into the distribution grid is solved and smart grid methodology is applied to the system. To summarize, coordination of protection system elements is realized via the smart grid concept and this is the major contribution of this study. Different operating conditions are tested for the WT, generator, and consumers. Relay coordination and operating conditions are optimized and stability of the system is achieved. Thus, the consumers will not have power outage while fault location is efficiently being cleared.

This study is the first step of a complex smart grid network that includes various renewable sources, communication systems, and adaptive relay protection solutions. In future studies, the grid will be equipped with the mentioned elements and an extended network will be used for more complex analysis.

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