Adaptive Relay in Microgrid - Hardware Implementation with User Interface

Vinod V and U Jayachandra Shenoy, Senior Member, IEEE
Department of Electrical Engineering
Indian Institute of Science, Bangalore
Email: vinodvc011@yahoo.com, ujs@iisc.ac.in

Abstract—The increase in percentage-wise proportion of Distributed Generations is a great boon to the end consumers. However, such developments lead to major protection challenges in distribution systems. This paper describes the hardware implementation of an Interface relay, which is connected at the point of common coupling (PCC) in the micro-grid. The work includes the development of a Graphical User Interface (GUI) for the effective utilization of the proposed relay. The various functions implemented in the Interface relay are Synchronization, Islanding and bidirectional over current protection. The program is coded in the micro-controller using embedded C software. Phase locked loops (PLL) with moving average filter algorithm is used in the relay to attenuate the 100Hz ripples introduced during unbalance in the supply voltage. In the case of bidirectional over current protection, different relay operating time has been set for faults occurring in forward and reverse direction. The proposed Interface relay implemented has been rigorously tested to validate the performance based on simulation of the test signals using National Instruments waveform generation module and using Lab-View software. The test results clearly indicate the successful performance of the proposed scheme for micro-grids.

Keywords: Interface relay, micro-controller, islanding, synchronization, circuit breaker, phase locked loops

I. INTRODUCTION

Conventional power system alone cannot meet the ever growing needs of electrical power in the world in a reliable manner. Under these circumstances, large penetration of Distributed generators in the distribution level of the power system network is a great boon to the consumers. Now a days, the consumers install Distributed Generators (DGs) at their site to cater the critical loads. Frequently, the micro-grid works in both the modes of operation. In the island mode of operation, micro-grid operates independently without connecting to the grid and feed the critical load termed as intentional islanding and the other mode is based on the grid operation of the micro-grid. These configurations will change the relaying parameters set by the grid authorities due to the bi-directional flow of power. Additionally, frequent synchronization process and detection of islanding should be considered for implementing these features in the relay. The relay should perform accurately for all the operating conditions and faults. The relay is normally connected at the point of common coupling (PCC). The islanding method described in [1]-[3] clearly explains the theory behind the passive and active islanding techniques and simulation results are presented. Working of the synchronized reference Phase Locked Loops (PLL) [10] to find the frequency, phase angle and voltage magnitude is discussed in [4]-[6], but the error occurring in the calculation of phase angle during unbalance in the system is not provided. The need of the hour is to implement a digital relay suitable for micro-grids [11] and should support functionalities such as synchronization, Islanding, bidirectional over current protection and ability to work properly during unbalance in the supply. This paper describes the hardware implementation of an Interface relay, which is connected at the point of common coupling (PCC) between the main grid and the micro-grid. The work includes the development of a Graphical User Interface (GUI) for the effective utilization of the proposed relay. The relay has been implemented on TMS320f28377S floating point micro-controller based hardware platform. The hardware details and its integration has been explained in the Interface relay section (Section-III) of the paper. The subsequent section discusses about the interactive graphical user interface (GUI) software developed to communicate with the Interface relay. Remaining three sections clearly explain different functions incorporated in the relay with suitable logic. The program is coded in embedded C.

II. INTERFACE RELAY - HARDWARE DETAILS

Fig. 1 shows the Interface relay design comprising of complete hardware circuitry including the control circuit and the high power switching circuit. To understand the working of the Interface relay, each of its subsystems is explained in detail. To perform many functions in one processor effectively and efficiently, high performance micro-controller TMS320f28377S based hardware platform has been used to implement the relay. Texas Instruments TMS320f28377S is a 32-bit, 200MHz single precision floating point processor having 12-bit Analog to Digital Converter (ADC) of 12 channels and also supports three numbers of 12-bit buffered Digital to Analog Converter (DAC) to generate the output wave forms for monitoring purpose during testing of the relay program. An interface card suitable for the relay has been designed for communication through LCD user interface.

The interface relay has voltage and current sensors [5], a single relay card and DC voltage supply card to derive 24V,
5V and 3.3V for digital and analog circuits. The voltage sensor card can receive three high voltage signals up to 1000V and convert to unipolar scaled down voltage signals ranging from 0V to 3V suitable for the micro-controller. The two Hall Effect sensors reside in the current sensor card supports input currents up to 20A which can be converted to a corresponding voltage ranging from 0V to 3V compatible for the micro-controller hardware.

The complete control over the circuit breaker (CB) is achieved with the help of three relay cards namely Trip, Close and Open relays. These relay cards receive control signals from the micro-controller to operate the transistor switch to perform various actions on the circuit breaker. During faults, the micro-controller issues a logic HIGH signal, which in turn will connect 230V AC supply to energize the shunt trip coil residing inside the circuit breaker so as to open the breaker quickly, within 10ms. The trip signal from relay card also provides 230V AC supply to the motorized circuit breaker to close the circuit breaker during the time of synchronization. The Close/Open status of the circuit breaker under program control is very important to take appropriate decision to carry out various operations and during the time of maintenance. An auxiliary switch provided inside the compartment of the circuit breaker having normally open switch is used to provide close/open signal under program control to set the position of the main contacts of the CB. The schematic diagram of both the shunt trip coil and auxiliary switch is shown in Fig. 2. Fig. 3 shows the internal compartment view of the CB which houses a shunt trip coil and auxiliary switch.

The specification details and the electrical wiring circuit of the motorized CB is given in [9]. The motorized CB is an accessory, by means of which it is possible to remotely control the ON and OFF positions of the breaker. The current sensor card used is not able to measure the high fault current of the order of kilo Amperes. Three CTs of 200/5A rating, are used to convert the current through the main distribution line. The secondary of the CT is shorted with a wire of resistance less than 10mΩ. From the data sheet, it is observed that the over current limiting factor for a burden resistance $R_b<10\text{mΩ}$ is found to be around 40. Thus, CTs can faithfully reproduce the fault currents of the order of 8KA without getting into saturation.

**III. INTERFACE RELAY - GRAPHICAL USER INTERFACE**

The relay can perform well, if there is a provision to change various relay settings and there should be a facility to monitor various electrical parameters. Graphical User Interface (GUI) for the proposed relay is designed with the help of Visual C# and the relay communicates with the external device using Universal Asynchronous Receiver-Transmitter (UART). Fig. 4 shows six different GUI blocks to set the parameters for over current relay, communication, Islanding and power limit as well as for monitoring electrical parameters and for displaying fault information.

The monitoring block of GUI enables measurement of electrical parameters such as voltage, frequency, power factor, active and reactive power at both the grid and micro-grid side. Important fault informations such as the location of the fault either on the main grid or in the micro-grid side of the network, identification of faulty phase, trip time etc. can be obtained from fault information block of GUI. Over current relay parameters such as Pick up value, Time Setting Multiplier, selection of relay characteristic curve and Instantaneous setting can be set from the over current setting block of GUI. Also, flexibility is provided to enable the relay to function during forward and reverse faults and this feature is programmed in...
the over current setting block. Based on the setting, same relay can work in different modes, such as bidirectional, unidirectional and non-directional relay. Enabling of the port for data transmission between GUI block and the microcontroller at desired baud rate can be set in the relay communication setting block. Using Island setting block of GUI, one can set the upper and lower limit of voltage and frequency as well as tripping time of the relay. Power limit setting block of GUI is used to set active and reactive power flows both in the forward and backward directions. Whenever the power flow is above the threshold level, the relay will operate the circuit breaker after the predetermined trip time.

IV. SYNCHRONIZATION LOGIC

In a micro-grid environment, the main grid is connected with local power system comprising of distributed generators and both the systems are interconnected at the point of common coupling (PCC). So, the process of synchronization is very important to ensure that there are no oscillations and transients during the synchronization. The electrical parameter like voltage magnitude, frequency and the phase angle information should be calculated accurately from the three phase voltages for proper synchronization. This is achieved using phase locked loops (PLL) to convert the incoming three phase voltages to a stationary-frame and then to a rotating d-q frame. The block schematic of PLL featuring the conversion of voltages from stationary to rotating frame components with moving average filter design is shown in Fig. 5. The judicious selection of the value of \( K_p, K_i \) in the PI controller helps to find the angular frequency \( \omega \) of the input supply. Simple integration is enough to find out the phase angle of the input voltages. Meanwhile the resultant voltage magnitude is projected both on the d and q axis. The reference value \( V_{qref}=0 \) and the phase angle feedback acts in such a way so to reflect the voltage magnitude completely on the d-axis. After tracking, the PLL gives the accurate voltage magnitude, frequency and the phase angle information.

The SRF-PLL works smoothly when there is no unbalance in the voltage supply. In practice, however in power system networks, unbalance can occur resulting in the introduction of negative sequence voltages. Due to this, 100Hz ripple will be present in the d & q axis voltage in a 50Hz system which in turn causes error in phase angle calculation. To nullify the effect of this ripple, a Moving Average Filter (MAF) is introduced after the \( V_d \) calculation as shown in Fig. 5. Fig. 6 shows the detailed structure of the MAF. The basic technique adopted is to find the average of the present sample plus the previous nine samples of the voltage signal. The signal is sampled at the rate of 1KHz using down sampler with the help of timer interrupt combination in the TMS320f28377S micro-controller. The complete design for the PI controller of the SRF-PLL with moving average filter is given in [8].

The synchronization logic is explained with the help of Fig. 7. Algorithm corresponding to the logic is implemented using embedded C program in TMS320F28377S floating point microcontroller. Both the Grid and DG side voltages are scaled down to lower levels and converted to unipolar signals suitable for the processor with the help of two voltage sensors. PLL with moving average filter algorithm convert these signals to corresponding voltage magnitude \( V_d \), frequency \( Freq \) and phase angle \( \theta \). The difference between the respective values of each of the parameters are checked and if the difference is less than a set value and within the tolerable limits, a logic HIGH signal is issued to AND gate as shown in Fig. 7. Logic HIGH generated by all the inputs to AND gate is sufficient to close the switch S2.

Fig. 8A shows the simulated LABVIEW generated scaled values of phase-A voltage signals at both the grid and DG side. When the two waveforms are perfectly matched, a SYNC signal is generated to close the switch S2. Fig. 8B depicts phase angle outputs from PLLs of both the grid and DG side and these plots are obtained from the DAC output of the processor. These waveform plots are obtained by selecting the scale as \( 2V = 360^\circ \).
V. ISLANDING LOGIC

One of the main functions of the Interface relay is to prevent the formation of unintentional island. Intentional and unintentional islanding [7] can be explained as referred to the Fig. 10. Suppose the grid side Circuit breaker S1 is opened by the grid authorities for the maintenance of the feeder and the situation may arise with switch S2 closed. This condition will lead to an unintentional island as shown with large shaded area in Fig. 10. This inturn will result in the energization of the feeder by the DG and violate the safety precaution of the grid authority. The interface relay should act during such conditions to open the switch S2 and thus forming an intentional island indicated by the small shaded area as shown in Fig 10.

The logic circuit for the islanding operation is explained with the help of Fig. 11. Here, the voltage signal obtained from the DG side of the switch S2 is used to extract DG side voltage magnitude and frequency information by applying the PLL with MAF algorithm. Due to the opening of switch S1, there is a mismatch of active and reactive power between the DG source and the load. Because of this difference in powers, there is a corresponding change in the input voltage and the frequency. Voltage and frequency check logic compares the changed values of voltage and frequency with the stipulated IEEE 1547 standard levels and the trip signal is generated in case there is a mismatch. The trip signal is issued after the predetermined trip time, thus forming the desired intentional island.

For testing the validity of tripping time in accordance with the IEEE 1547 standards, three phase voltages are generated using National Instruments Digital to Analog converter module. The voltage and frequency of the signals are then varied using LABVIEW software. Fig. 9 shows the snap shots of the trip time obtained due to the variation of voltage and frequency. The variation of voltage by 115% and 80% of rated value results in trip times of 1 sec and 2 secs respectively. Also, it is found that the change in the input signal frequency from the nominal 50Hz to 49.4Hz and 53Hz generate a trip signal after 0.2sec.

VI. BIDIRECTIONAL OVER CURRENT PROTECTION

Normally in distribution feeder, the fault current flows only in one direction, but due to the proliferation of DGs, the fault current may flow in both directions. For the smooth functioning of micro-grid, the protective relay should be able to operate independently during both directions of current flow during faults. This function is implemented in the proposed interface relay and tested using voltage signals. The direction of fault current can be checked by calculating the active power flow using the real and imaginary part of both current and voltage phasors. Fourier full cycle algorithm calculates the real part (V_s and I_s) and imaginary part (V_i and I_i) of both current and voltage phasors. In accordance with the phasor diagram shown in Fig. 12, the complex form of voltage and current are represented as follows:
Then the real power $P$ is calculated using the expression, $P = V I^* = V_m I_m \cos(\theta) + V_c I_c$, which is mathematically equal to $V_m I_m \cos(\theta - \phi)$. If the calculated value of current magnitude is greater than the pick up value, the sign of power $P$ is negative which means the fault is behind the relay. Otherwise, the fault is in the forward direction. The bidirectional over current detection logic is tested by applying the equivalent scaled value of the actual voltage and current magnitude to the interface relay. Phase angle between the $V$ and $I$ signal during the fault is selected by outputting corresponding, voltage and current signals using the National Instruments DAC hardware and using Lab View software.

To examine the reverse relay characteristics, the following parameters are selected for the over current relay.
The interface relay for micro-grid applications has been designed and developed. The interface relay is placed at the point of common coupling (PCC) between the main grid and the micro-grid. Various functions such as synchronization logic, Islanding logic and bi-directional over-current protection are programmed in the relay using embedded C code. The moving average filter as part of PLL design ensures that the relay works satisfactorily even during unbalance in the supply voltages. The interface relay is developed using high performance TMS320F28377S microcontroller based hardware platform. The relaying scheme includes voltage and current sensor cards, motorized circuit breaker and associated circuitry as subsystems. An interactive Graphical User Interface (GUI) software has been developed using visual C# which supports communication feature for relay setting, monitoring and measurement of both the main grid and micro-grid side parameters such as voltage, current, frequency, power factor, active and reactive power. The proper working of the complete scheme has been tested under different operating and fault conditions. The test signals are generated using National Instruments 16-bit DAC hardware module and Lab-View software. The results obtained are highly encouraging and the protection scheme which supports different functionalities is suitable for applications under microgrid environment.

**REFERENCES**

[9] Catalog Molded Case Circuit Breaker Siemens 04/2015