Implementation of Automatic Transfer Switch using Three Phase Voltage Vector Phase Lock Loop

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Emergency standby generators play a crucial role in ensuring uninterrupted power supply during grid failures or unexpected outages. They provide an essential backup to maintain critical operations in various settings, including hospitals, data centers, and industrial facilities. The need for these generators arises from the increasing dependence on electrical systems for daily functioning, where even brief power interruptions can lead to significant economic losses, safety hazards, or compromised operations. The automatic transfer switch (ATS) in emergency standby systems improves reliability and ensures the continuity of vital services during power failures by facilitating the transfer of load from the primary source to the emergency source and vice versa. However, there are two critical scenarios which causing temporary power interruptions: first, the delay in connecting the generator to the load when utility power fails, and second, the transition from generator to utility power upon restoration. These temporary disruptions can also significantly impact industries and other critical applications that depend on continuous power supply. To address these challenges, the focus has shifted towards minimizing the delays in transferring the loads. This paper addresses the solution to the second scenario by focusing on eliminating the momentary power outages during the transition from generator to utility power. A solution is proposed using an ATS equipped with synchronization control implemented through a three-phase voltage vector-based phase-locked loop, effectively preventing disruptions.

Keywords: automatic transfer switch, synchronization, Phase Lock Loop (PLL).

Introduction

The synchronization of an alternator with a power grid is vital to ensure that the voltage, frequency, phase sequence, and phase difference are properly aligned with the existing power system. There are two types of synchronization procedures: Manual Synchronization and Automatic Synchronization. In Manual Synchronization, the synchronization of generators with the grid relied on manual intervention, which was prone to human errors with serious consequences for the power system.

In case of emergency standby generators system delays in transferring the load from generator power to utility power and vice versa are two scenarios which results in temporary power interruptions, which can significantly impact industries and critical applications that require continuous, uninterrupted power [1-8]. Here are some potential consequences:

- Operational Disruptions
- Loss of Productivity
- Data Loss

- Equipment Damage
- Safety Risks

Hence, an automatic synchronization process is necessary to overcome the aforementioned issues of manual synchronization and control methods to provide uninterrupted power supply to load without any delays in Automatic Transfer Switch (ATS) operation.

Literature Review

The uninterrupted power supply is crucial for various daily activities to avoid sudden disruptions caused. Such interruptions can have severe consequences, endangering the lives of patients in hospitals, compromising research materials in laboratories, due to the absence of power for electronic and communication equipment.

Backup power plants are typically available in industries to ensure continuous processes, as well as in commercial, governmental, hospital, and university sectors to guarantee the continuation of important activities [1]. If the service interruption is planned in advance, affected customers may receive notifications to prepare themselves. However, in cases of unforeseen network faults, transfer of loads from the utility power source to the emergency power supply becomes necessary [2-10].

Normally, a knowledgeable operator is required to manage the generator and transfer the load to the generator source. However, the operator may not always be in close proximity to the generator during a service interruption. Therefore, an automatic control system, known as the ATS, can replace the role of the operator[11-14]. Transfer switches facilitate the transition of loads between normal and emergency power sources, offering open or closed transition options.

- Open Transition: An open transition is a break-before-make transfer method. In this process, the transfer switch disconnects from one power source before connecting to the other.
- Closed Transition: A closed transition is a make-before-break transfer method. In this process, the transfer switch establishes a connection to a second power source before breaking the connection with the first power source[15].

However, there is very little papers analysis the ATS control techniques to alleviate the delay during the transition of load from primary source to the emergency source and vice versa. This paper presents the designs for automatic synchronization of generator with grid and an ATS that will give the solution for eliminating the temporary power interruption during the transition from generator to utility when the utility restored its power.

System Description

The system includes an electric utility service and a generator for normal and emergency power sources respectively. This system arrangement is typically referred to as an emergency standby generator system.

The three phase generator with a rated voltage of 400 V (line to line voltage) and frequency of 50 Hz, supplying load is intended to connect with the balanced three phase electrical grid using proposed ATS as shown in the Fig.1. Generally, during the operation of ATS, temporary electrical power disruption to the load may occur during the following situations,

- Transition of load from grid to generator
- Transition of load from generator to grid

The electrical power disruption to the load during the transition of load from generator to grid can be eliminated with the proposed system. The proposed system requires six voltage sensors, microcontroller and triggering circuits to operate the existing ATS, which may cost less than 300 USD.

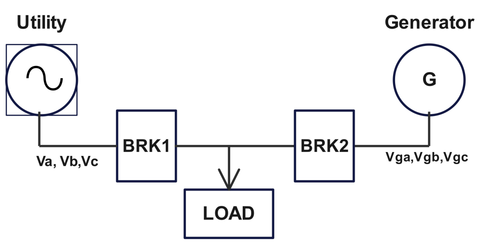

Figure 1: Connection diagram of generator with the grid

Methodology

Automatic Transfer Switch

When the grid is offline

When the electrical grid is unavailable, breaker will disconnect the grid and connect the generator with the load.

When the grid is restored.

When the grid is restored, the synchronization process takes place to avoid temporary power interruption and will connect the grid with the generator after proper synchronization. Once the grid begins supplying the load, the torque of the generator will be adjusted to bring its power output to zero using the proposed torque control method. The generator can then be safely disconnected from the grid when its power contribution has been reduced to zero.

Proposed Control Techniques

Park Transformation

The Park transformation is a mathematical transformation that converts three-phase AC quantities (Va,Vb,Vc) into two-phase DC-like quantities (Vd,Vq) where Vd is direct axis component and Vq is quadrature axis components. This transformation is commonly used in the control of three-phase electrical systems.

The Vq is used to match the generator's phase with the grid. The Park transformation equations are implemented as shown in the Figure 2.

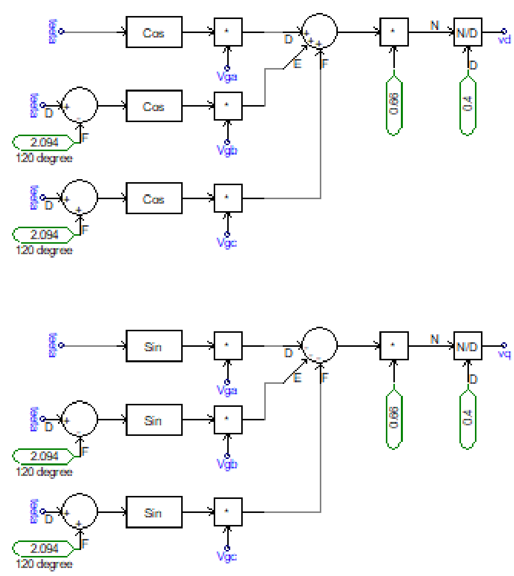

Figure 2: Park Transformation to derive Vd and Vq

Phase Lock Loop (PLL)

The PLL generates a signal that tracks the phase of the input voltage using the Phase Vector Technique which is given in Fig. 3. This ensures that the phase angle of the generator voltages match with the phase angle of the grid voltage.

The PLL control loop plays a key role in ATS operation by providing a smooth, filtered, and fast-tracking phase angle detection mechanism.

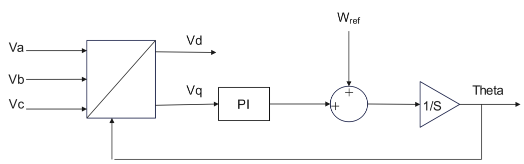

Figure 3: PLL control loop

The key to achieving proper grid synchronization is accurately tracking the phase angle of the utility grid voltages. This is accomplished by regulating the quadrature component of the voltage, denoted as Vq.

By feeding the Vq signal into a Proportional-Integral Controller(PI Controller), the controller is able to make fine adjustments to closely match the phase angle of the grid. The output of the PI Controller is then added to the reference angular frequency, which is set to 314.15 rad/s (50 Hz).

This combined signal, representing the desired synchronous angular position, is then fed into an integrator. The integrator takes this input signal and produces the actual 'theta' value, which corresponds to the instantaneous angular position.

Torque control

If the quadrature axis component (Vq), derived from the grid angle and generator voltage, is not close to zero, there is mismatch between the phase angle of generator and the grid side voltages. To bring Vq to zero value, it is required to adjust the torque of the generator based on the Vq value. If Vq is positive, the generator is leading the grid. To reduce the leading phase angle and to bring Vq closer to zero, generator torque has to be decreased. If Vq is negative, the generator is lagging the grid. In this case, we should increase the generator torque to reduce the lagging phase angle and bring Vq closer to zero. This can be achieved using the torque control which is given in Fig. 4.Tsync is the torque needed to obtain synchronization.

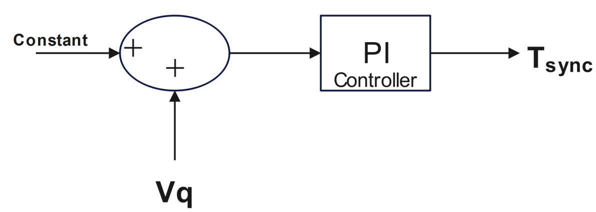

Figure 4: Torque control to correct Vq

Hysteresis control

Hysteresis control is a type of variable-structure control that uses a hysteresis comparator to generate the switching signal for the circuit breaker. This will prevent any on off malfunction when a signal passes its threshold values.

Hysteresis Comparator: It has two threshold levels - an upper threshold and a lower threshold, creating a hysteresis band, which prevents the malfunction. It compares whether the input voltage is within the threshold values.

Switching Logic: the input signal (voltage) needs to cross the upper or lower threshold by a certain margin before the output (circuit breaker state) is allowed to change. This helps to filter out its operations from a small fluctuations or noise in the input signal.

The 'Vq' is then given to the hysteresis buffer with the threshold values (+0.05 to -0.05). When the input signal is inside the hysteresis region, it will pass the control signal to close the breaker and vice versa. Thus, when the breaker is closed, generator will be connected with the grid. The circuit breaker logic is:

0 = ON (close)

1 = OFF (open)

Power reduction of generator

As the proper synchronization is achieved, the grid will be connected with the generator. At this point, the generator needs to be disconnected from the system. This can be accomplished by gradually reducing the power output of the generator to zero, and then proceeding to disconnect the generator from the system. The step-by-step process involves initially matching the generator's output with the grid, and then transitioning to fully relying on the grid power by ramping down the generator's contribution to zero, before finally isolating the generator from the overall power network.

Results & Discussion

An emergency standby generator system was modelled using PSCAD simulation. The simulation results are studied and summarized below.

Phase Lock Loop (PLL)

Fig. 5. Shows the exact locking of phase angle (theta) with sinusoidal voltage waveform.

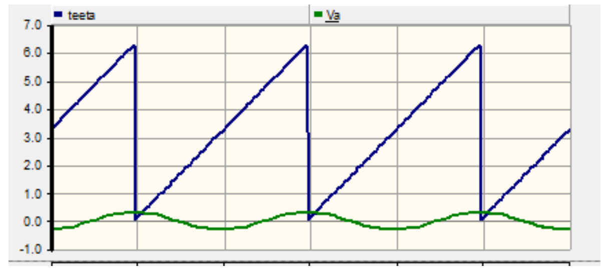

Figure 5: Derived theta from grid voltages using PLL

Park Transformation:

In Fig. 6. 'Vd' represents direct axis component (green) and 'Vq' represents the quadrature axis component (blue).

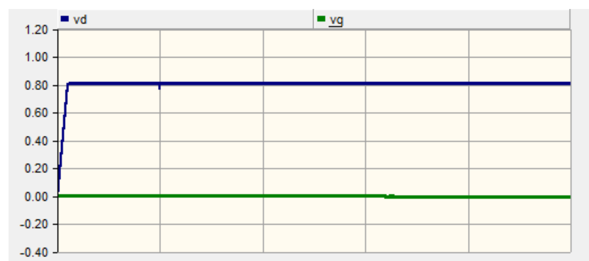

Figure 6: Variation of Vd and Vq.

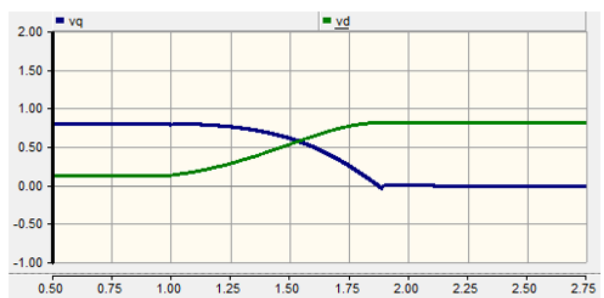

Figure 7: Variation of Vd and Vq, initially when 30 degree phase shift between grid and generator voltages after implementing torque control

Torque control

In the Fig. 7. Vq reached zero around 1.8 second. Synchronization is achieved within one second. It ensures that the torque control regulates the Vq by adjusting the torque of the generator.

Hysteresis control

The analysis of the Fig. 8. reveals that when the Vq is out of the hysteresis region, it passes the signal to open the circuit breaker and vice versa.

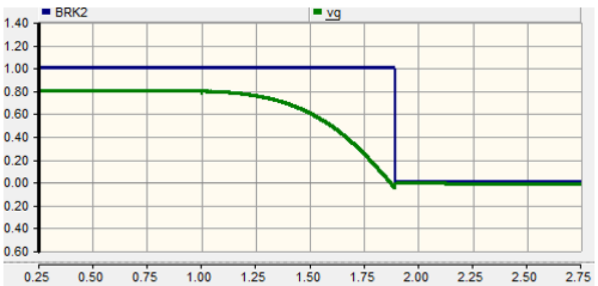

Figure 8: Operation of breaker with 30-degree jump in grid voltage after implementing torque control

Power reduction of generator

When the power of the generator is brought to zero by adjusting the torque, the breaker 1which is connected with the generator can be disconnected. This can be observed in the Fig. 9.

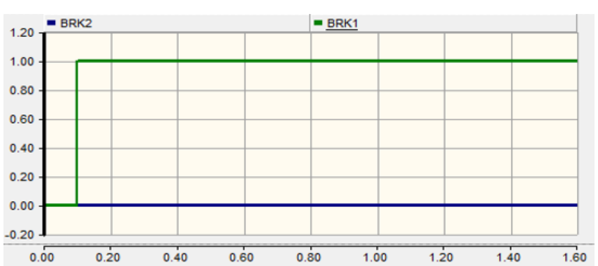

Figure 9: Operation of breaker 1 and breaker 2 after synchronization

Conclusion

This paper outlines the design of an automatic grid synchronization system developed using PSCAD software. The proposed technique utilizes a three-phase voltage vector-based phase-locked loop, which considers all three phases simultaneously for synchronization. This approach ensures smooth and reasonably quick locking of synchronization, making it more effective than existing alternatives.
Moreover, it entirely eliminates temporary power interruptions during the transfer of load from the generator to the grid. It also prevents any malfunctions that may occur in loads like motors, when switching between sources by achieving proper synchronization through an Automatic Transfer Switch. This synchronization control ensures a smooth and timely transition between the generator and grid power sources, thereby minimizing disruptions during the load transfer. These are remarkable outcomes from this research.

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