An Approach to Improve Power System Resiliency in Grid-Connected Wind Turbine Generator Power System

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Abstract: - A new concept of optimal Point-on-wave (PoW) switching to curtail the power system resiliency of the wind power plant connected with a transformer is presented. Optimal PoW switching targets are determined using mathematical analysis and tested on the simulation model. The said simulation model has been developed using PSCAD/EMTDC software for system parameters of the existing wind power plant electrical network of Gujarat, India. The proposed optimal PoW-based method is capable of reducing the magnetizing inrush current exceptionally. Further, the proposed technique is also efficient in smoothening the voltage profile and decreasing harmonic contents in the supply, which improves the power quality of the wind power plant electrical network. Afterwards, to demonstrate the proposed technique based on optimal PoW, a hardware model has been developed in a laboratory environment. The result of the hardware model provides a promising outcome as proof of the proposed technique. In the end, a comparative evaluation with a recently developed technique is also carried out where it has been observed that the proposed technique is providing superior results.

Key-Words: - Point on the wave, Wind power, switching transients, Wind turbine to grid-connected transformer, the magnetizing inrush of the transformer, harmonic contents in magnetizing inrush.

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1 Introduction

To minimize the level of greenhouse emissions and other environmental problems, power engineers around the globe are continuously improving sustainable solutions to promote green energy, [1]. In this regard, solar, wind, and biomass power plants have been found the most trustworthy options to replace as a substitute for the fossil fuel-based conventional energy sources, [2]. It is to be noted that wind power plants have achieved huge growth in the field of sustainable energy across the world. Further, asynchronous Wind Turbine Generators (WTG) have attained higher priority in comparison with other peer generators in recent decades due to exponential growth in power electronic devices. [1], [3], [4],. However, the main disadvantage of such types of WTGs is their poor responses to voltage and frequency profiles during switching and load variation, [5], [6].

Owing to uncertainty in the weather conditions, the power generation of the wind plants varies by a large amount. Subsequently, the penetration of the wind power plant-based energy sources in the conventional grid causes frequent switching operations. These frequent switching operations cause power quality issues at the distribution level

[1], [7], [8]. Thereafter, an approach to improve power quality for wind-based distributed generation systems using Lorentzian norm-based adaptive filters has been discussed in [7]. However, the selection of parameters for adaptive features is very critical in this method. Though the above-proposed methods have provided power quality solutions, these methods have not brought out a reliable solution in the case of magnetizing inrush which has been produced during switching of WTG.

Afterward, CIGRE working group carried out a detailed study of power resiliency problems on WTG considering the real-time system in the UK, [9]. In the above discussion, it is to be observed that WTG has been connected to a conventional grid at an extra high voltage level using a step up transformer. In this case, the transformer causes a high magnetizing inrush current during energization which is drawn from the WTG. Subsequently, this event leads to the development of a voltage dip in the distribution network which may cause adverse effects on the equipment working in the same network, [9]. Additionally, the level of harmonic contents at the Point of Common Coupling (PCC) in the distribution network also increases owing to high inrush current, [10]. Moreover, the dc component of inrush current further causes saturation in the instrument transformer connected to the bus of the distribution network, which may lead to the mal-functioning of the protective system.

To minimize the level of inrush current (LIC) during the energization of the transformer in the grid-connected WTG network, PoW switching techniques have been suggested in [11], [12], [13]. The application of PoW technique to minimize the switching transient levels during the energization of various power system equipment have also been discussed in [14], [15], [16], [17]. Further, the effect of operating time variation of circuit breaker has been considered during the application of PoW switching for energization of power system components as explained in [18].

Brunke and his team members have presented the application of a PoW strategy to mitigate the inrush current during the energization of the power transformer based on residual flux levels, [19], [20]. Thereafter, Chandrasena *et. al* performed the PoW switching technique for the energization of the transformer on a real-time platform, [21]. However, the effect of statistical and systematic variations of the circuit breaker is required to minimize the inrush current in above proposed techniques. In [22] and [23], heuristic search-based algorithms have been presented to mitigate the mal-operation of the differential relay during the energization of a transformer. Though these algorithms offer high accuracy, the choice of parameters is the key limitation of the heuristic-based techniques and also increases the protection cost for the distribution network. In the above methods, the level of residual flux in the core, resistances of the primary and secondary windings, magnetizing characteristic of the iron core, and switching instant of the source side voltage play a vital role in deciding the amount of inrush current, [24].

Owing to the low moment of inertia and low level of short circuit current capacity compared to conventional power stations, the wind farm has been considered a weak source of power generation, [24]. During random energization, a wind farm to grid-connected transformer draws high inrush current and subsequently, it develops voltage dip and other power resiliency problems in the distribution network. Further, the dc offset component of the inrush current causes saturation in the core of the instrument transformer, which further leads to the development of mal-operation in the protection system. Thus, to mitigate the magnetizing inrush current in the wind power plant, an application of PoW for the energization of Wind Farm to a connected Transformer has been discussed in this paper. Initially, the frequency of supply has been determined using the zero-crossing technique. Afterward, the first phase to be closed has been decided based on the peak of the reference phase for different types of transformer configuration, which results in a reduction in inrush current, voltage dip, and harmonic contents. Thus, the proposed method indicates improvement of the power resiliency problems in grid-connected wind power system networks.

2 Effect of Random Energization of the Transformer Connected with WTG

A wind farm to grid-connected transformer draws high inrush current during random energization. In turn, it also produces voltage dip and other power resiliency problems in the distribution network. Further, the dc offset component of the inrush current may also lead to saturation in the core of the instrument transformer. Henceforth, to determine the LIC, voltage dip harmonic contents & dc offset, a simulation study in the PSCAD/EMTDC software package has been carried out and the results have been depicted in Figure 1. Figure 1(a), (b) and (c) show the LIC, voltage dip and fundamental, harmonic & dc contents respectively. It is to be noted that the first phase has been switched on at zero crossing instant and the remaining two phases after 5 ms. Further, the short circuit capacity of the source has been considered as 5 kA for WTG during the simulation study.

It has been observed from Figure 1(a) and (b) that the LIC and voltage dip during the energization have been found as 2.89 pu and 0.827 pu, respectively. Further, Figure 1 (c) shows the level of fundamental component (I1), 2nd to 7th harmonic contents (Ih2 to Ih7), and dc offset (Idc) of the magnetizing inrush current of phase-c which attains the highest level of inrush current in a simulation study. It has been observed from Figure 1 (c) that the levels of Ih2 and Idc attain high levels of magnitude. Thus, from Figure 1, it has been observed that LIC, harmonic components, and dc offset lead to create voltage dip, power quality issues, and power system resiliency problems in the distribution network.

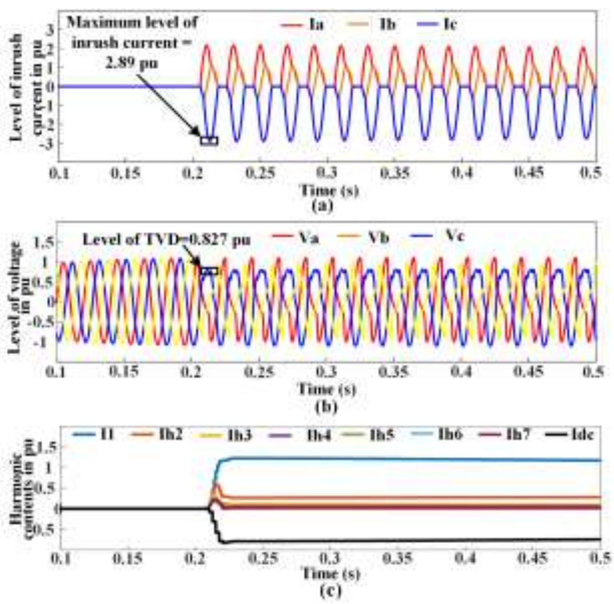

Fig. 1: Level of (a) inrush current, (b) voltage dip, and (c) harmonics contents during energization of wind to grid connected transformer

3 Optimal PoW-based switching Techniques

To illustrate the Optimal PoW-based switching technique for improving power system resiliency, the network configuration, mathematical derivation of PoW targets, and proposed techniques have been described in the following sub-sections.

3.1 Network Configuration

The Single Line Diagram (SLD) of WTG connected with the grid existing in Gujarat, India has been shown in Figure 2. The whole system illustrated in Figure 2 has been implemented in the PSCAD/EMTDC software package. As shown in Figure 2, the wind farm consists of ten units of 1.5 MW each. Hence, the total generation offered by the wind farm has been considered as 15 MW. Further, the voltage generated by WTG is 0.4 kV which is stepped up to 11 kV using transformer T1, which is connected in Δ/Y configuration. Then, to connect this wind farm to the grid, two other transformers T2 (11/400 kV) and T3(11/230 kV) are connected in parallel. The parameters of these transformers have been mentioned in the Table 1. It is to be noted that at any instant, only one of the secondaries (either 400 kV or 230 kV) remained in connection, and at any point in time, any transformer (either T2 or T3) remained in the circuit.

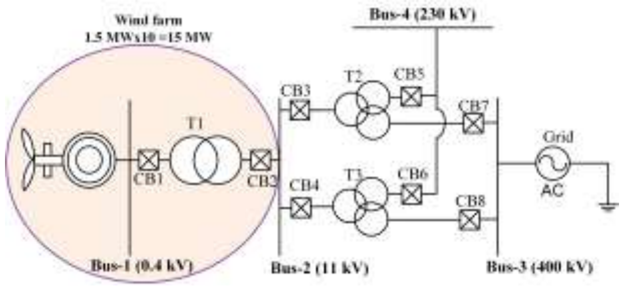

Fig. 2: Single line diagram of WTG existed in Gujarat, India

3.2 Mathematical Derivation of PoW Targets

To determine the PoW closing targets for the energization of Wind Farm to Grid Connected Transformer, a Resistance-Inductance (R-L) series circuit connected with an ac source supply has been considered. In this case, the supply voltage at any instant is represented by eq. (1).

$$V(t) = V_m \sin(\omega t + \psi_v) \quad (1)$$

Where, V_m is maximum voltage, ω is phasor rotating frequency and ψ_v is the energization instant of the circuit.

In case of R-L series circuit, the power factor angle (ψ_i) of the circuit is determined by eq. (2)

$$\psi_i = tan^{-1}\left(\frac{\omega L}{R}\right) \qquad (2)$$

When an R-L series circuit has been switched on, it develops two components namely (i) steady-state component and (ii) exponentially decaying transient component as indicated in eq. (3).

$$i(t) = \frac{V_m}{Z}\left\{[\sin(\omega t + \psi_v - \psi_\iota)] - \sin(\psi_v - \psi_\iota) * e^{t/\lambda}\right\} \qquad (3)$$

It is to be noted from eq. (3) that the transient turns to be zero when ψ_v=ψ_i. This indicates that when the switching angle is becoming equal to the power factor angle, the transient term attaints zero magnitude. Hence, to minimize the level of the switching transient, the switching instant is to be determined from the power factor angle. In the case of a transformer, the inductive reactance (ωL) of the winding is very high in comparison to winding resistance (R). Hence, power factor angle ψ_i becomes equal to $\pi/2$ as per eq. (2). Therefore, if the switching instant ψ_v has to be made equal to $\pi/2$ (i.e. instant to attend the peak of reference voltage), the magnitude of current becomes almost equal to steady state current during switching on the instant. This criterion has been utilized in the proposed technique to mitigate the magnetizing inrush for improving power system resiliency.

Table 1. Details of wind farm to grid-connected transformer

Knee point voltage	1.1 pu
Magnetizing current	1% of rated current

3.3 Proposed Technique

Figure 3 shows a flowchart of the proposed technique. Whenever a change-over command is detected by the circuit breaker, the data regarding the transformer connection is collected. To decide the deliberated time delay by the PoW device for the circuit breaker closing instant, it is essential to find the zero-crossing instant of the reference voltage (i.e. voltage of phase-a for three-phase system in this paper). Finding the zero-crossing instant is not only deciding the time delay for the circuit breaker closing instant but it also benefits in finding accurate frequency whose variation is found continuously during power system operation. Thus, the frequency has been found based on the time lapse between two consecutive zero crossing instants.

After finding the frequency and converting this frequency into a timestamp, the deliberate time delay between the first peak to be closed on phase – a and the last zero crossing instant has been calculated, [25]. Subsequently determining the deliberate time delay, the PoW based closing targets for different types of connection of the transformers have been identified. Thereafter, based on the type of transformer connection, the PoW closing commands have been given to the closing coils of the different phases of the circuit breaker. As mentioned, firstly, phase–a has been energized, and thereafter, the remaining two phases have been switched on after 5 ms depending upon the type of transformer connection.

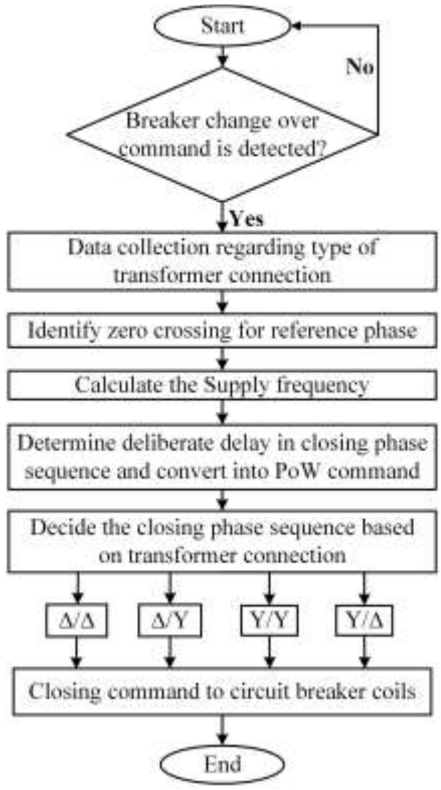

Fig. 3: Flowchart of Proposed method

4 Results and Analysis

4.1 Simulation Results

To test the performance of the proposed technique, a simulation study on SLD shown in Figure 2 has been carried out using PSCAD/EMTDC software. As shown in Figure 2, transformer T1 has been energized by closing the circuit breaker CB1. Before providing a closing command to coils of CB1, the frequency of the supply has been determined by using the zero-crossing technique. Hence, based on the measured frequency, the time delay between the first peak of phase – a has been found out. After the said time delay, the PoW command to the circuit breaker CB1 has been given for energization of Δ/Y connected transformer T1 on phase – a. Further, the remaining two phases (phase – b and then phase – c) have also been energized as mentioned in the proposed method. The obtained results of magnetizing inrush, voltage, and harmonic contents have been depicted in Figure 4. As shown in Figure 4 (a), the LIC has been observed to be 0.025 pu which is quite less than 2.89 pu which has been found during random switching. Moreover, the voltage profile has also been found to be 1 pu in all phases of the transformer during energization compared to 0.827 pu in the case of random energization. Hence, the voltage dip has been reduced in this case and power system resiliency has been improved. Furthermore, the fundamental, harmonic contents and dc decaying has been also observed as indicated in Figure 4 (c). As shown in Figure 4 (c), the magnitude of all the mentioned quantities has been reduced drastically using the proposed PoW technique.

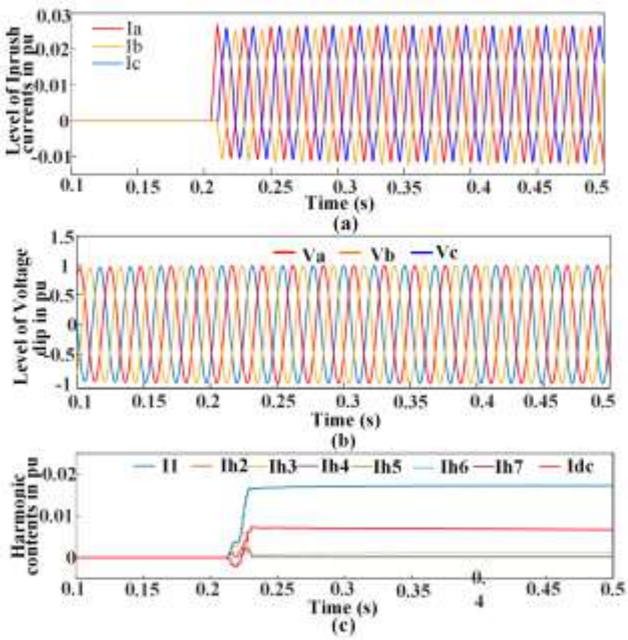

Fig. 4: Level of (a) inrush current, (b) voltage dip, and (c) harmonics contents during energization of wind to grid connected transformer using proposed technique

4.2 Hardware Setup

A prototype to validate the proposed technique has been developed in the laboratory and the obtained result is shown in Figure 5. Figure 5(a) illustrates the block diagram of the hardware setup. As shown in Figure 5 (a), the current signal has been collected and they are sent to the zero crossing detection circuit. The said circuit consists of a combination of a rectifier and optocoupler which rectifies the input current signal and finds the interruption of input current at zero crossing. This zero crossing is sensed by Arduino and processed to calculate the frequency. In Arduino, software coding has already been executed for zero crossing detection, calculation of frequency, determination of optimal closing instant, and triggering signal to solid state device using IDE open-source software in computer system. Hence, after determining the frequency of the supply accurately, the time taken to reach the peak of voltage has been calculated and the optimal switching instant has been found. At this instant, Arduino provides trigger commands to the solid state switch at the peak of the voltage wave in the transformer.

Figure 5(b) illustrates the snapshot of the hardware setup which shows the computer system, zero crossing detector circuit, Arduino circuit, solid state switching, transformer (which is to be energized), and digital signal oscilloscope. On receiving the triggering signal, the solid-state device turns on and the transformer energizes. This energized current signal has been captured in a digital signal oscilloscope and is shown in Figure 5 (c). As depicted in Figure 5 (c), the LIC is found to be 0.085 pu which indicates the satisfactorily low value of inrush in comparison to random energization of the transformer. The details about apparatus used for hardware set up is shown in

Table 2.

Table 2. Details about hardware setup

Apparatus	Specifications
Transformer	1.5 KVA, 440/230 volts
Solid state device	Triac, BTA41, 600 volts
Microcontroller	Arduino controller

4.3 Comparative Analysis

The proposed method based on Optimal PoW-based technique has been examined in connection with other published research articles based on [10] and the results are depicted in Table 3. It has been noticed from Table 3 that LIC is relatively lower in the proposed technique in comparison with published articles for simulation as well as hardware results. In addition, it is also observed that the voltage profile has also been improved satisfactorily during simulation. The same result has also been achieved with hardware setup.

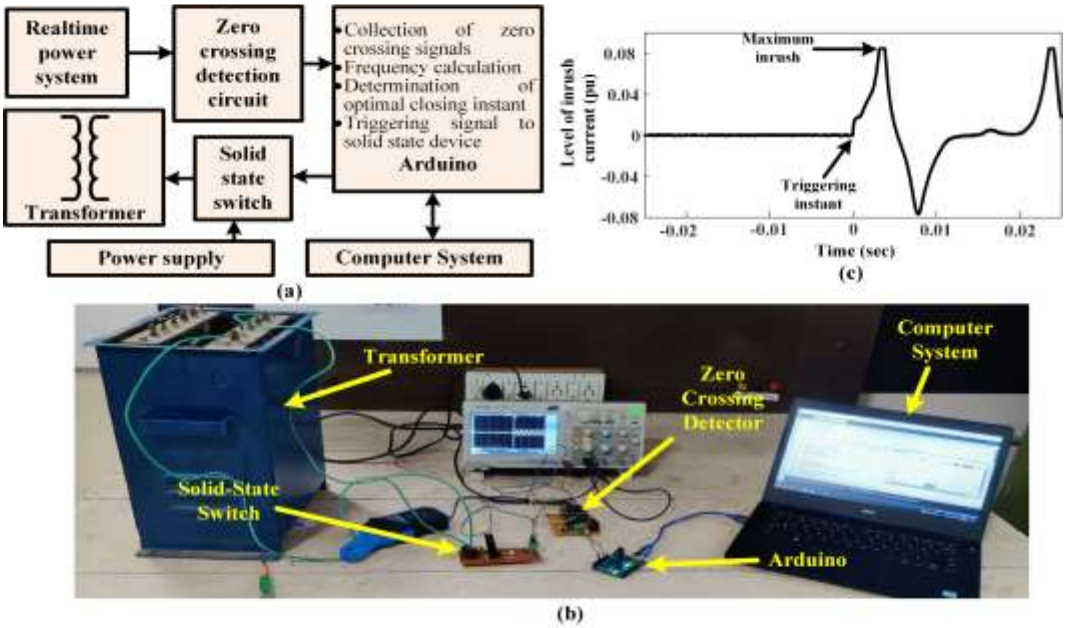

Fig. 5: Hardware setup: (a) Block diagram, (b) Snapshot of setup, and (c) LIC

Table 3. Comparative analysis of suggested scheme with published research article, [10]

Sr. No.	Nomenclature	Proposed Technique	Published research article in [10]
Simulation Results			
1	LIC (pu)	0.025	1.44
2	Voltage level (pu)	1	0.993
Hardware Results			
1	LIC (pu)	0.085	0.54

5 Conclusion

A new optimal PoW-based technique is presented to improve the power system resiliency in the wind power plant connected with the transformer. Initially, optimal PoW instant has been found using mathematical analysis. Afterwards, a simulation model for the wind power plant electrical network of Gujarat, India has been developed in the PSCAD/EMTDC software package. During simulation, the application of optimal PoW instant is remarkably reducing magnetizing inrush, improving voltage profile, and decreasing harmonic contents of current. Further, the analysis of the proposed technique has also been carried out with the help of hardware setup in a laboratory environment whose outcome exceptionally increases the reliability of the proposed method. In the end, a comparative analysis of the proposed technique with the recently presented method provides improved results. In the future, work will be performed to develop an algorithm for carrying out PoW switching using the Internet of Things and Artificial Intelligence.

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Contribution of Individual Authors to the Creation of a Scientific Article (Ghostwriting Policy)

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Conflict of Interest

The authors have no conflicts of interest to declare.