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A Transient Component-Based Technique for Fault Detection in Distributed Generation Systems

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***Abstract*— In this paper, transient current and voltage responses, caused by low and high impedance faults in a power system with distributed generation (DG) systems, are investigated. The proposed approach utilizes a novel transient index (TI) based on the voltage during fault at the point of common coupling. The proposed technique uses voltage signals at DG connection point to provide the value of TI. The performance of the proposed scheme is evaluated on a power system consisting of photovoltaic systems and wind turbine generators as the case study by using a real-time simulator. The simulation results, which will be included in the full paper, show the fast and reliable operation of the proposed fault detection technique as compared to the existing fault detection methods, not only for low impedance transient faults but also for high impedance faults.**

Keywords—transient, distributed generation, fault., protection,

I. Introduction

By emphasis on sustainability of power systems, the design, planning, and operation of electric power grids are transferred to use different distributed power resources such as photovoltaic (PV) systems, and wind turbine (WT) generation as distributed generation (DG) units [1]-[3]. In the U.S over the last decade, there has been a significant increase in penetration of DGs, such as PVs, being integrated into power systems. The total installed PV in the U.S. was 25 GW by 2015 and the expected penetration of PV is to be approximately 302 GW by 2030 [4]. The integration of DGs in power systems makes a bi-directional current contribution during a fault event. Therefore, the traditional fault detection equipment e.g., overcurrent relays cannot operate well in these systems [5].

Efficient fault detection of power systems with distributed generation units is highly desired for utility companies. In recent years, due to the increasing penetration of converter-based DGs, the total inertia of power systems is dramatically reduced. This phenomenon causes to have a lower rise time in fault currents, and it impacts the stability of the power systems during a fault [6]. Consequently, this highlights the need for a quick fault detection scheme in modern power systems [7].

In terms of fault detection of DGs in low-inertia power systems, low-impedance faults (LIFs) have a high magnitude transient fault current caused by a high value of current in low-resistance path and discharging of capacitors of converters at the same time, which could damage the converters within a few milliseconds [8]. Moreover, high impedance faults (HIFs), which have low fault current magnitude, may cause failure in the operation of fault detection devices [9]. Consequently, an efficient fault detection scheme should be equipped with both LIFs and HIFs detection functionalities.

Several types of research have been performed on fault characteristic analysis and fault detection methods of DGs in power systems. The study presented in [10] minimizes the variation in fault current level after installation of DGs by minimizing the change in the bus impedance matrix through optimal sizing of a fault current limiter. However, installation of fault current limiters is costly and only affects the operation of protection systems on sending the trip signal successfully, not reducing the operation time of fault detection devices. Optimal sitting and sizing of DGs to minimize the impact of DGs on installed fuses and relays is suggested in [11]. In most planning issues, the size and place of DGs cannot be changed, and therefore, the method in [11] cannot be implemented practically.

Recent studies have attempted to investigate the impact of converter designs of DGs on the current contribution during short duration faults, and the possible ability on aiding the fault detection units [12]. However, most control and design schemes on converters are related to DG fault ride-through (FRT) capability [13], which mainly ensures the power system stability after fault isolation and system recovery [14]. Fault detection based on voltage measurement is able to overcome the challenges on the fault detection in power systems equipped with multiple inverter-based DGs [15]. In [16], a fault detection method by using modal transformations on the voltage of the system during fault is reported. Therefore, this method uses the disturbances reflected in the DC *d-q* values, and the faulty situations are detected by comparing the real-time DC *d-q* and reference values. Moreover, the use of total harmonic distortion of voltage in DG units is utilized in [17] to detect faults. However, the aforementioned methods cannot detect HIFs and have a low-speed performance during LIF detection.

To address the research gaps mentioned above and propose a fast and reliable fault detection method for power systems with high penetration of DGs, a novel criteria transient index (TI) fault detection technique is proposed which uses the voltage behavior of the system during fault. Considering the transient behavior of fault voltage during both high and low impedance faults, a localized method for multiple faults in DGs is proposed based on voltage transients during fault. Consequently, the fault transients are analyzed and detected quickly by real-time voltage measurements. The proposed method is tested under different LIF and HIF conditions by real-time simulations, using an OPAL-RT setup, to investigate the most accurate fault detection time in different events. The results will be included in the full paper.

II. Fault Detection Technique

The proposed fault detection technique requires real-time measurement of local voltage at the DG bus. To detect

LIF and HIF faults, the proposed technique utilizes a new criterion, as peak of TI, which is computed from measured three-phase voltages, as shown in Fig. 1. The TI reflects the events which confirm the presence of a fault in the system by causing severe transients in the power systems. Then, the fault detection sends the trip signal to the related circuit breaker (CB) through a proper communication channel to isolate the faulty point. For the local fault detection, the maximum value of the absolute sum of the difference between the actual and regenerated voltage samples is computed over a cycle [18], which is defined as TI. The detailed calculation methodology is provided as follows.

The DG bus voltage including the decaying DC component during a fault can be modeled as

$$v_n = V_m \sin(n\omega t + \theta) + ke^{-n\frac{t}{\tau}} \tag{1}$$

where V_m is the amplitude of voltage, ω is the frequency of the system, θ is the phase angle, t is the sampling time interval, τ is the time constant of the DC decaying component, and k is the magnitude of DC decaying component during fault. To estimate the fundamental components of (1), it can be modified to the following equation [19]:

$$[A][X]=[B] \tag{2}$$

where,

$$[A]=\begin{bmatrix} \sin(\omega t) & \cos(\omega t) & 1 & -t & t^2 \\ \sin(\omega 2t) & \cos(\omega 2t) & 1 & -2t & (2t)^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \sin(\omega(N-1)t) & \cos(\omega(N-1)t) & 1 & -(N-1)t & ((N-1)t)^2 \\ \sin(\omega Nt) & \cos(\omega Nt) & 1 & -Nt & (Nt)^2 \end{bmatrix} \tag{3}$$

$$[X]=[V_m\cos(\theta) \quad V_m\sin(\theta) \quad k \quad \frac{k}{\tau} \quad \frac{k}{2\tau^2}]^T$$

$$[B]=[v(t+t_0) \quad v(2t+t_0) \quad \cdots \quad v(Nt+t_0)]^T$$

in which N represents the total number of samples per cycle. Then, the unknown vector is calculated by the least square

method as follows

$$[X]=([A^TA]^{-1}.A^T)[B]=A^{\dagger}[B] \tag{4}$$

where $[A]^{\dagger}$ is the pseudo inverse of [A]. The estimated least square for the fundamental components can regenerate the voltage signal. Therefore, the regenerated data samples can be obtained by

$$[\hat{B}]=[A][X]=[A](A^{\dagger}[B]) \tag{5}$$

where, $[B]^{\dagger}$ is the regenerated data, and the difference between $[B]^{\dagger}$ and the original input voltage signal can be calculated by

$$[E]=[\hat{B}]-[B]=([A][A^{\dagger}]-I)[B] \tag{6}$$

where,

$$[E]=[e_1,e_2,...,e_n] \tag{7}$$

Therefore, the TI can be defined by summation of absolute values of e over one cycle as

$$TI=\sum_{n=1}^{N}|e_n| \tag{8}$$

During a fault, the presence of a DC decaying component is prominent in the faulty phase, then a significant TI can be found in the faulty phase. To calculate a suitable TI threshold for detecting fault events, the largest value of TI is calculated for the largest overload condition, normally 120% of rated current [20]. Therefore, to distinguish the faulty and overload events, the following constraint should be satisfied

$$TI > TI_{Overload} \tag{9}$$

where, TI is the real-time value of the index, and $TI_{Overload}$ index is the value of index, or threshold, during maximum overload. With a TI value greater than the threshold, the fault detection device will detect the faulty event. To achieve more reliability of the protection system during the fault, selecting a threshold for TI is vital. The selection of the threshold depends on system configuration and depends on the transient characteristics, inertia, and fault resistance. However, the presence of a low level of DC decaying voltage and current during HIFs may cause the TI fault detection unit to maloperate. To overcome this challenge, it should be noted that the value of TI can be categorized for different disturbances, as shown in Fig. 2. As the value of the threshold is selected based on the large overload conditions, the value of TI will be higher for HIFs and LIFs, as they increase the TI to a higher value compared to overload conditions.

A. Maintaining the Integrity of the Specifications

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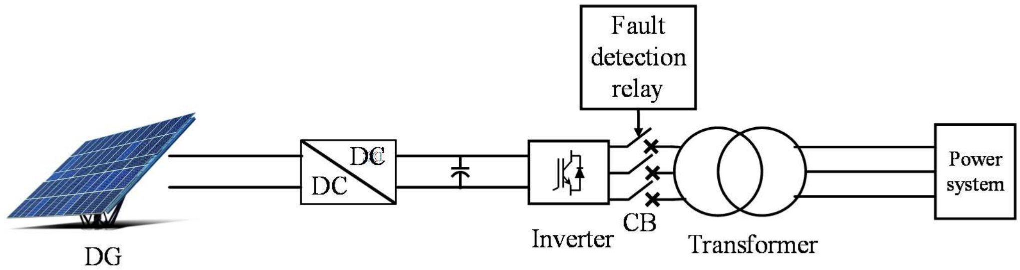


Fig. 1. Implementation of fault detection scheme

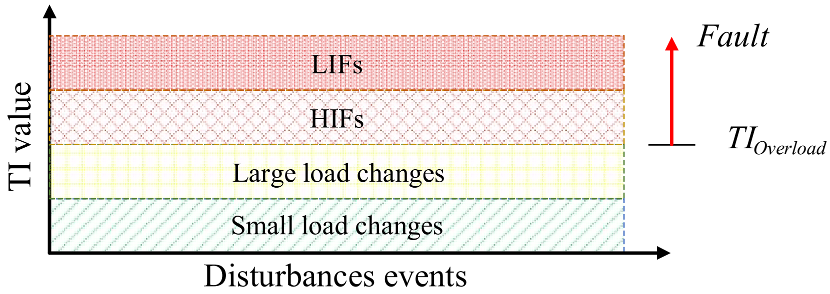


Fig. 2. TI values for different disturbance regions

III. Simulation

To evaluate the performance of the proposed fault detection technique, different test conditions are simulated on the simple PV system of Fig. 1, which is connected to the grid. During these conditions, the transient voltage signals are retrieved from the relays placed at the inverter end. The TI values, fault current, and voltage signals during a LIF with 0.1 Ω at $t = 1$ s are shown in Fig. 3. The results show the speed and accuracy of the proposed method during LIFs, in which LIF is detected within approximately 1 ms. In the scenario, a HIF with fault resistance of 10 Ω at $t = 1$ s is simulated, and the TI values, fault current, and voltage signals are shown in Fig. 4. Therefore, the proposed transient-based method detected the HIF within 2 ms.

The value of Threshold or $TI_{Overload}$ is selected based on the border of fault classification. As shown in Fig. 2, the highest value of load change is defined based on 120% of the rated normal current. Therefore, in an event of large load change, the value of $TI_{Overload}$ is calculated, which is defined by the $TI = 10$, as shown in Fig. 3. Consequently, the highest value of fault resistance for HIFs is also determined as an event that causes the fault current close to 120% of normal current.

In case of disturbances, for example, high amplitude harmonics, the fault detection relay should distinguish it with LIFs and HIFs, and avoid sending the trip signal to circuit breakers. Thus, a harmonic event at $t = 1$ s is simulated, and the current and TI values are shown in Fig. 5. Therefore, due to the lower value of TI than $TI_{Overload}$, the fault detection system will not send any trip signal to circuit breakers.

IV. Conclusion

A transient-based technique using TI derived from a three-phase voltage was proposed in this paper to detect faults in power systems equipped with DGs. To detect faults in these systems, the voltage from DGs is accessed locally. The fault detection methodology has been developed for critical conditions such as LIFs and HIFs, and the proposed method provides a reliable and fast fault detection method. The proposed scheme will be tested in a real-time simulation environment by OPAL-RT to demonstrate the high speed of the proposed method during both LIFs and HIFs. Furthermore, the method will be tested under different disturbances, such as noise, overload, and bad calibration of sensors. Moreover, the selectivity of the proposed method will be investigated to ensure having the lowest isolated zones during faults.

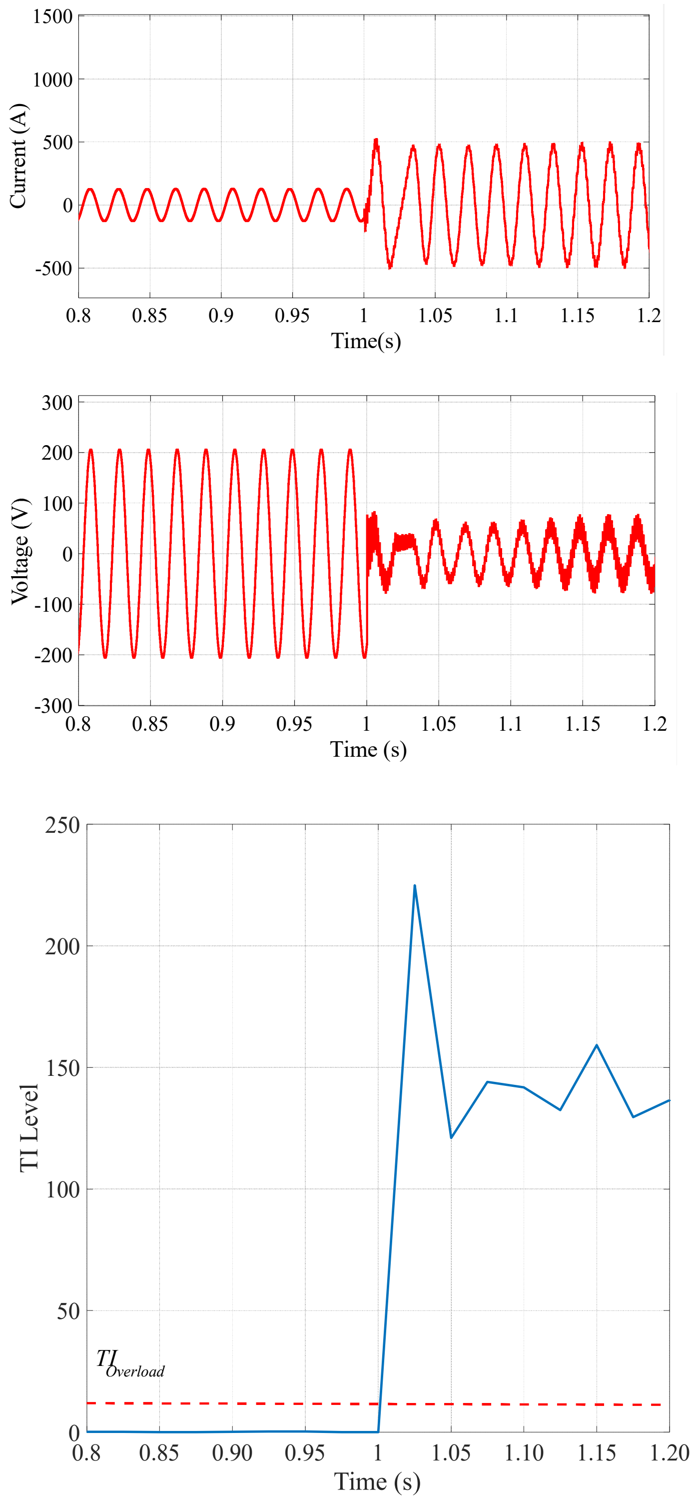
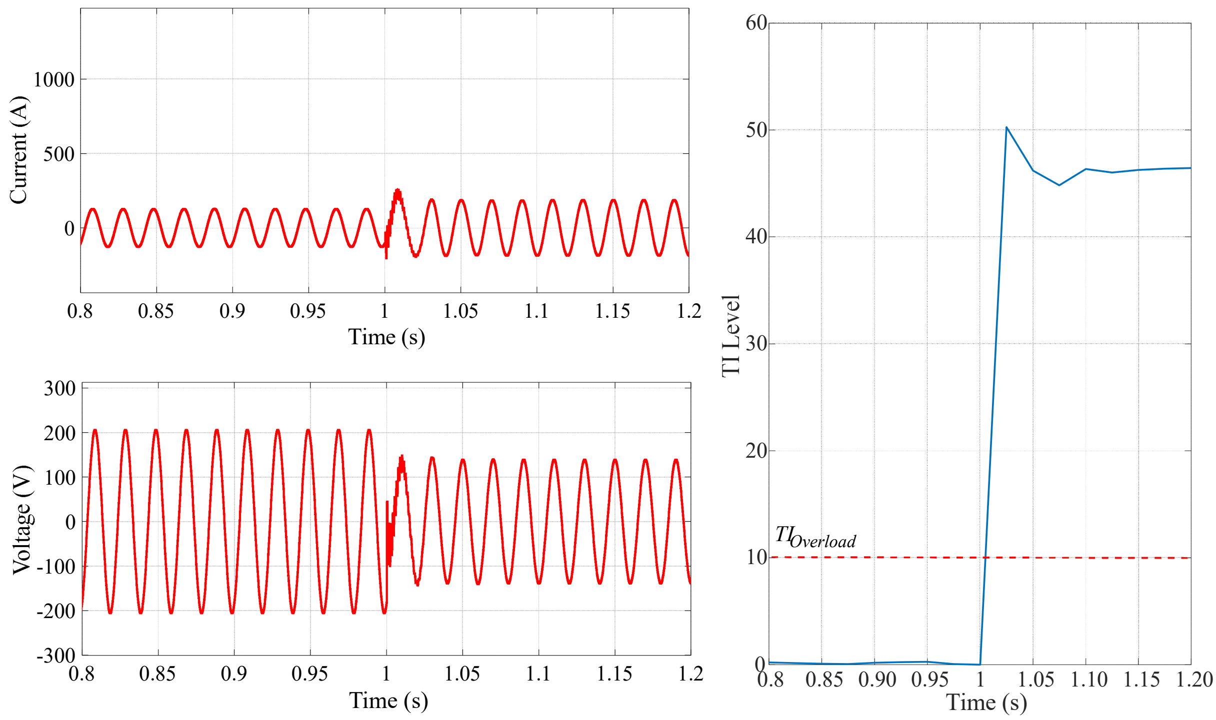
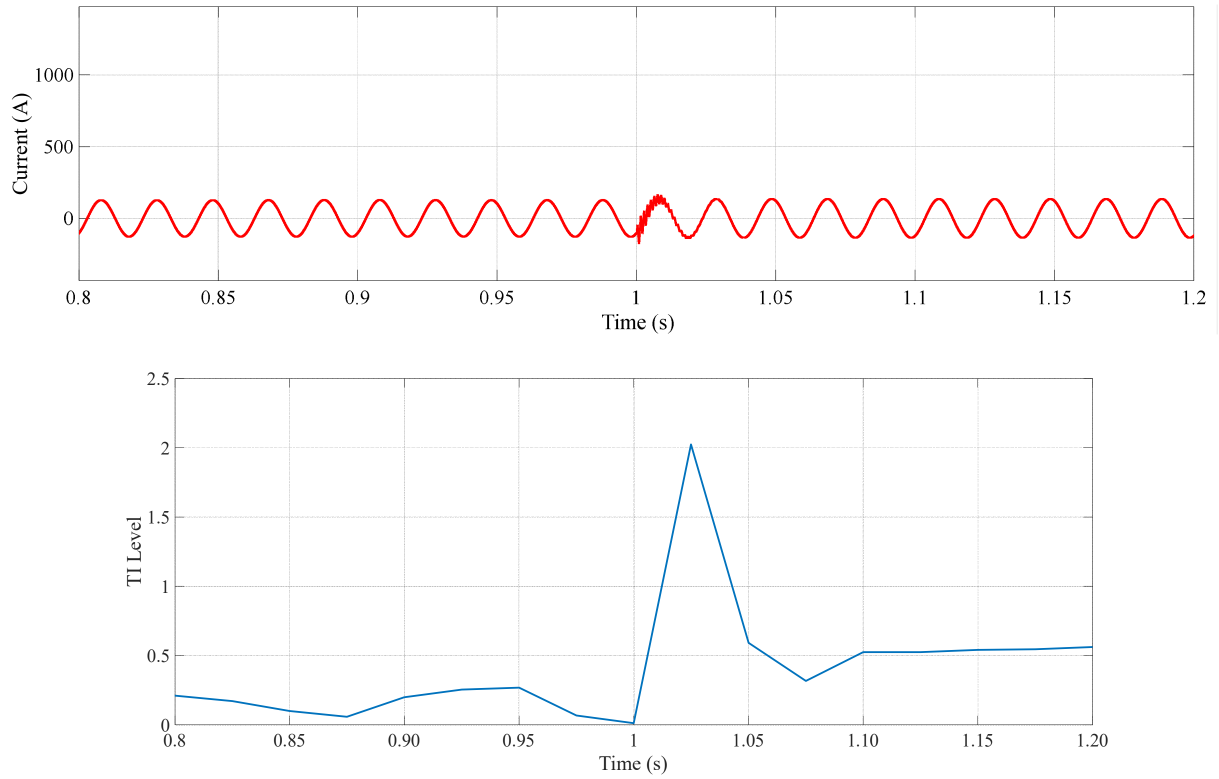


Fig. 3. Relay signals during a LIF at $t = 1$ s with fault resistance of 0.1 Ω (a) fault current, (b) voltage signal, (c) TI.





(b)

Fig. 5. Relay signals during a harmonic event at t = 1 s (a) current, (b) TI.

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