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Impact of converter-interfaced renewable generations on breaker failure protection of the emanant transmission lines

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Abstract
The presence of Converter Interfaced Generations (CIGs) poses significant challenges to traditional protection schemes. This paper studies the impact of CIGs on the Breaker Failure Protection (BFP) of transmission lines emanating from CIGs. The instantaneous overcurrent (50BF) setting and reset time of BFP have been investigated. Fault current contribution of CIGs is usually comparable with load currents. Low fault current contribution by CIGs may lead to significant loss of security of BFP because of the existing practice of using lower setting for 50BF. This paper proposes a voltage-dependent adaptive setting of 50BF element to enhance the security of BFP schemes while maintaining dependability. Use of voltage helps in differentiating loads from fault situations. In traditional power systems, CT subsidence current is known to delay the reset of BFP schemes. The impact of low fault contribution by CIGs on the reset time of BFP has been studied. Mathematical expression for CT subsidence current, which influences the reset time, has been derived. It is observed that the BFP reset may not be delayed if the fault current seen by the breaker is low due to the presence of CIG. Discussions on the dependability and security of proposed 50BF setting are also presented.

1 | INTRODUCTION

Power generation from conventional sources like fossil fuels is widely being supplemented by renewable power sources. The projected level of renewable penetration in the United States by 2050 is around 80%, with nearly 50% from wind and solar sources [1]. At the global level, the renewable sources are expected to produce around 60% of the total electrical power generation [2]. Large-scale renewable power plants are being installed at the transmission level. Power electronic converters are commonly used as interfaces to control the power output of these plants. Power electronic switches with high switching frequencies result in fast control and complex dynamics [3]. The grid integration of Converter-Interfaced Generations (CIG) poses significant challenges to the existing protection schemes. The semiconductor switches of converters have limited overloading capabilities [3]. Hence, the power converters are designed to limit the fault currents flowing through them. This leads to the reduction of the fault current contribution by the CIGs [4]. Novel relaying algorithms for primary protection of transmission lines are being developed by the research community to address the protection challenges in presence of CIGs. The issues with the distance protection of transmission lines emanating from CIGs are discussed in [5]. The authors of [5] observe that the converter parameters such as the current limit settings influence the impedance seen by the relay. In some situations, the apparent impedance is much different from the actual fault impedance. This may result in reach issues during both Zone-1 and Zone-2 faults. The solution identified for the above problem has been proposed in [6] by the same research group. The impact of CIGs on distance relay and directional relay based on fault current characteristics have been studied in [7] and [8], respectively. In [7], it has been observed that the limited short circuit current and the controlled initial phase angle may lead to loss of reliability of distance relays. An improved scheme based on time delay and zero-sequence impedance has been proposed in [7] to address this issue. In [8], it is observed that the fault current characteristics display...
significant low-frequency harmonics and unbalanced sequence impedances. This may lead to the failure of fault-component-based directional relays. High-frequency impedance-based protection scheme has been proposed as a solution in [8]. The impact of the renewable generation on the coordination of directional relays has been presented in [9]. To obtain the new relay coordination status, two different approaches depending on the protection scheme already in place have been presented in [9]. The performance of distance relays during grid side fault on the protection scheme already in place have been presented in [9]. Literature [11] studies the impact of large-scale wind farm penetration on conventional distance relays. In [11], a new protection scheme has been proposed for uncompensated/compensated double-circuit transmission lines using current measurements from single end. Maloperation of directional pilot protection scheme on a transmission line connected to a wind farm is discussed in [12]. It has been observed that the difference in the positive and negative sequence components during a fault leads to the failure of fault phase selection. A voltage-based fault phase selector has been proposed in [12]. The problem in phase selection logic of transmission line differential protection for lines connected to wind farms has been discussed in [13]. A voltage-based adaptive technique has been proposed as a solution. The impact of power electronic converters on transmission line ground fault protection along with solution is discussed in [14]. Here, it has been observed that the negative sequence relaying loses its reliability as the power converters usually do not provide negative sequence current during system unbalances. Pilot protection schemes with echo logic have been proposed as a solution in [14]. An adaptive distance relay setting for lines emanating from wind farms is proposed in [15]. The performance of distance relays on ac grid with an offshore wind HVDC network is analysed in [16]. It has been shown that, with conventional relay setting, there could be reach issues due to the reactive power control of the converters. To overcome this, adaptive settings have also been proposed in [16]. An adaptive unit which modifies the distance relay tripping characteristics according to wind farm power output fluctuations using artificial neural networks has been proposed in [17]. The work in [18] addresses the Zone-1 reach issues of distance relays on transmission lines connected to induction generator-based wind farms. A permissive overreach transfer trip scheme along with fault current classification has been proposed as a solution in [18]. In summary, the major challenges encountered by the primary protection are:

- The short circuit current provided by CIGs is usually limited by the converter control.
- The limited fault current results in the apparent impedance seen by the relay which is far different from the actual fault impedance. This may lead to under-reach or over-reach operation of distance relays.
- The converters usually do not provide negative sequence current during unbalanced operating conditions and faults.
- The absence of negative sequence current during system unbalances may result in the failure of sequence component based ground fault protection of transmission lines.
- The superimposed positive and negative sequence impedances used in directional relays have their phase angles determined by the converter control. This may affect the functioning of fault-component based directional relays.

Existing literature predominantly focuses on the impact of renewable generations on the primary protection schemes. The impact of CIGs on back-up protection has not received much attention. The purpose of backup protection is to ensure protection during failure of primary protection. Primary protection might fail in clearing a fault because of the failure of measurement transducers, communication system, the relay or the circuit breaker [19]. Breaker failure protection (BFP) is an important backup protection which is employed to "take appropriate action to clear a fault when the breaker that is normally expected to operate fails to do so for any reason" [20]. The motivation behind this work is to study the impact of CIGs on the BFP of transmission lines emanating from CIGs.

A circuit breaker (CB) may fail to operate due to trip coil failure, contact failure, interrupting component failure or low dielectric gas pressure. Adequate breaker failure protection scheme is thus required for reliable back-up protection of the power system. Depending on the topology of the power system network, other CBs must be tripped to isolate the fault [20]. Common BFP practices in utilities are discussed in [21]. In [21], it has been observed that most of the BFP misoperations have been false tripping rather than false no-tripping. Security of a BFP scheme is thus extremely important. [22] analysed the reset time of breaker failure algorithms employed in transmission lines sourced by synchronous generators. The reset was observed to be delayed due to the presence of subsidence current. Two different methods have been proposed in [22] to enable fast resetting. The work in [23] also addresses the 50BF reset delay. An algorithm to overcome this problem has been proposed in [23]. These works are applicable to systems with synchronous generators. Currently, there is a lack of literature on the impact of CIGs on BFP.

This paper focuses on the impact of CIGs on the BFP of transmission lines emanating from CIGs. The instantaneous over-current setting and reset time of BFP are carefully investigated. Existing BFP schemes usually employ instantaneous over-current element (50BF) to detect whether the breaker has failed to operate after a specified time. The setting of 50BF element poses significant challenge to the protection engineers. The 50BF element must be set below the minimum fault current [24] to ensure dependability. At the same time, the 50BF element must be set above the maximum load current [24] to ensure security. In traditional power systems, fault currents are usually significantly higher than the load currents. Still in some situations, the minimum fault current seen by a CB can be lower than the maximum load current [24]. In this case, the existing BFP schemes may lose security if 50BF is set below the minimum fault current. Existing BFP schemes usually use low setting [21, 24] for 50BF to achieve dependability while losing security. This is a limitation of the existing BFP schemes. The fault current contribution of CIGs is usually low. As a result, the breaker associated with the transmission lines emanating from
CIGs may see fault currents comparable to or lower than the load currents. Therefore, it becomes further difficult to differentiate load situation from fault situation using current values. In this scenario, it will be challenging to set 50BF while ensuring both dependability and security. There will be significant loss of security if low setting is used for 50BF. Loss of security may cause undesired operation of BFP leading to disconnection of large amount of components. The contributions of the paper are summarised as:

- Voltage dependent adaptive setting of 50BF element of BFP has been proposed to enhance the security of BFP schemes while maintaining the dependability. The setting of 50BF is changed adaptively based on bus voltage. Higher 50BF setting is used when the bus voltage is above a threshold and lower 50BF setting is used when the bus voltage is below the threshold. Use of voltage helps in differentiating a load from a fault situation. Discussions on the dependability and security of the proposed 50BF setting are also presented.
- The impact of low fault current contributions by CIGs on the BFP reset has been studied. In traditional power systems, the reset of BFP scheme gets delayed due to CT subsidence current. Existing literature does not provide mathematical expression for the CT subsidence current. This paper derives mathematical expression for the subsidence current from the CT circuit model. It is observed that the reset of BFP scheme will not be delayed if the fault current seen by the breaker is low due to the presence of CIG.
- The performance of the proposed 50BF setting and the argument related to subsidence current are supported using PSCAD simulations of a transmission system with CIG. Three existing BFP schemes are used for all the studies of this paper.

The rest of the paper is organised as follows. Section 2 gives an overview of the basic BFP schemes that are investigated in this work. The major aspects of a BFP scheme, the 50BF element setting and BFP reset, are discussed in this section. In Section 3, the performance of the existing BFP schemes is analysed in presence of CIGs. The effect of CT subsidence current on BFP reset time is presented for both synchronous generator and CIG. Section 4 presents the proposed voltage-based adaptive 50BF setting for BFP schemes to be implemented on transmission lines emanating from CIGs. The performance analysis of the proposed method is presented in Section 5. Section 6 presents a detailed discussion on the dependability and security of the proposed method in comparison with the existing methods. Section 7 concludes the work along with a discussion on the future research possibilities.

2 | OVERVIEW OF BREAKER FAILURE PROTECTION

The failure of a CB to operate upon initiation by the protective relay will let the fault to continue even though the relay has detected it correctly. To isolate the persisting fault due to CB failure, all adjacent CBs of local or remote substations are opened by BFP protection [21]. BFP schemes are implemented either on standalone BF relays or are integrated with the zonal protection relays [25]. There are two breaker failure modes. They are ‘Failure to Trip’ and ‘Failure to Clear’ [20]. In ‘Failure to Trip’, the CB contacts fail to open once the relay issues trip command. The possible reasons could be an open or short circuit in the wiring or in the trip coil. A mechanical problem in the CB may also prevent the contacts from opening. In ‘Failure to Clear’, the CB contacts open but the arc does not get extinguished and fault current continues to flow. This could be due to mechanical problems such as incomplete contact opening or dielectric problems such as contaminated oil or loss of vacuum. A method to detect ‘Failure to Clear’ has been presented in [26].

The paper analyses the breaker failure protection of transmission line emanating from CIGs. On detection of a breaker failure, the BFP scheme trips relevant adjacent CBs to isolate the fault. The security of a BFP scheme is very important as false tripping may result in extensive disconnection of components which may even lead to cascaded power outage [21]. A BFP scheme should also be highly dependable to prevent damages to the power system components.

2.1 | Overview of investigated BFP schemes

This section gives an overview of the BFP schemes investigated in this study. The basic BFP scheme is shown in Figure 1. Two inputs are used in the basic BFP scheme to monitor the state of the CB which is expected to clear the fault. The first input is a trip signal issued by the protective relay called Breaker Failure Initiate (BFI) signal. The second input gives information on the presence of current flow through the CB which indicates the persistence of fault. The overcurrent element 50BF is used for this purpose. The presence of both these signals triggers the timer 62-1. The continuous presence of both the inputs till the timer expiry will issue the BFP trigger signal [20]. This scheme is termed as ‘Basic BFP scheme’ and referred to as Scheme 1 here.

The BFP scheme shown in Figure 2 is used if there is a danger of the BFI not remaining present momentarily during the fault. This scheme is termed as ‘BFP scheme with seal-in’ and denoted
as Scheme 2. In the scheme shown in Figure 2, a seal-in signal is used to prevent the timer from resetting [20].

The performance of BFP schemes may be affected by many factors. CT saturation may result in dip in fundamental magnitude of current [27] that will result in reduction of secondary current below 50BF pickup level [24]. Performance deterioration of BFP may also stem from different breaker configurations and the use of single timer per protected bus [24]. These issues are addressed by using only BFI to start the timer. When the timer expires, the presence of 50BF signal will initiate the breaker failure output. This scheme is shown in Figure 3. This scheme is termed as ‘BFP scheme to ensure timer turn-on’ and will be denoted as Scheme 3.

In BFP schemes, use of the CB auxiliary contacts (52a and 52b) is usually avoided. In ‘Failure to Clear’ situations, the CB auxiliary contacts (52a and 52b) may change their states indicating breaker opening. Thus, the position of an auxiliary contact may not be a reliable indicator of a satisfactory breaker operation [20].

2.2 Setting of 50BF overcurrent element

Persistent high current situation in a CB is detected using overcurrent element (50BF). The pickup setting of 50BF should be done carefully to maintain both dependability and security of the BFP scheme. The 50BF pickup setting for BFP of transmission lines emanating from CIGs is discussed here. Literature [24] proposes the setting to be kept below the minimum fault current level. If the setting is kept below the maximum load level, then the 50BF element may pickup during load conditions. As a result, the BFP scheme will lose security in this situation [24]. In [21], 50% of minimum phase-to-phase fault current is recommended as the 50BF setting for transmission line CBs. The 50BF pickup threshold is suggested to be set at 10% of CT nominal secondary current in [23]. The 50BF setting is hence not agreed upon by the protection engineers. [21] opines that the setting cannot be universal and should be decided after a study on the system for different fault conditions. In general 50BF setting is kept low to achieve dependability at the cost of losing security.

2.3 BFP reset time

BFP scheme is initiated if the CB fails to clear the fault within a specified time. The BFP timer is triggered and the BFP trip signal is issued once the timer expires. If the CB clears the fault during timer counting, then the BFP scheme is deactivated by resetting the timer. A delay in this reset would lead to false operation of BFP, thus compromising the security of the scheme.

The persistence of fault is detected by the 50BF element by sensing the CT secondary current. Upon fault clearance, the primary current of the CT gets interrupted and ideally the secondary CT current should also drop to zero at the same time. However, the CT secondary current decays unidirectionally following the interruption of primary current. This current is called subsidence current. Subsidence current is caused due to the energy trapped in the CT magnetising branch [24]. Even when the primary current is interrupted at zero crossing, the secondary current may have positive or negative magnitude [29]. This secondary current will eventually subside with a time constant. The CT time constant dictates the decay of the subsidence current. CT saturation also leads to subsidence current in CT secondary [22].

The subsidence current phenomenon is shown in Figure 4 as depicted in [24]. A correct CB operation results in a sudden interruption of CT primary current during breaker opening, which causes subsidence current. The delay in the secondary current to fall to zero will result in 50BF being still picked up even though the primary current has been interrupted [24]. The reset time of current based BFP gets affected due to the presence of subsidence currents in CT [22]. The reset time typically gets delayed by 1-2 cycles [30].

3 PERFORMANCE OF EXISTING BFP SCHEMES IN THE PRESENCE OF CIGs

The performance of the existing BFP schemes for a CB located on a transmission line originating from a CIG is investigated in this section. All the discussed cases consider breaker failure due to the CB’s failure to trip.

3.1 Test system for BFP performance evaluation

The test system, shown in Figure 5 comprises of three synchronous generators (SG1, SG3, SG4) and one converter-interfaced wind generator (CIG2). Among the different types
of wind generator topologies, the Type IV wind generator with full converter interface has been used for CIG2. The topology of the wind generator is shown in Figure 6. The system parameters are taken from [5]. The wind generator and associated converter controls are modelled in accordance with [28]. The current control scheme for the inverter of CIG has been depicted in Figure 7. R25 and R52 are distance relays in Figure 5.

3.2 Fault levels in CIGs

The fault current levels may vary with different types of generation sources. SGs usually contribute significant fault currents. DFIG provide fault currents in the range 6-10 p.u. [31]. However, the fault contribution of CIGs can be as low as 110% of the rated current [32]. As a result, the fault current seen by a breaker on a transmission line emanating from CIG can be comparable with the load currents. Therefore, it becomes difficult to differentiate load situation from fault situation using current values. In this scenario, it will be challenging to set 50BF while ensuring both dependability and security.

3.3 Performance of BFP with existing schemes

Performance of three existing BFP schemes discussed in Section 2.1 has been evaluated in this section. The security and dependability of each of the schemes have been analysed. For this study, the 50BF pickup is set at 50% of the maximum fault current 1.5 p.u. The 62-1 timer is set to wait for 0.095 s considering a 5.75 cycles margin for a 3 cycles breaker [20]. The following two cases have been considered.

- Case 1: There is a A-G fault at F1. The CIG contributes 1.5 p.u fault current. Relay R25 issues BFI as expected.
- Case 2: There is no fault in the system. Load current seen by breaker CB25 is 1 p.u. Spurious BFI signal gets generated and fed to the BFP schemes.

3.3.1 Basic BFP scheme (Scheme 1)

Figure 8 presents the performance of Basic BFP scheme for Case 1 as described above. As the 50BF is set at 0.75 p.u, Scheme 1 performs satisfactorily. Dependability is maintained in this case. Figure 9 presents the performance of Scheme 1 for Case 2 as described above. In this case, 50BF picks-up even though there is no fault as the 50BF is set below load current. In presence of spurious BFI signal this scheme operates in no-fault situation. As a result, this scheme loses security.

3.3.2 BFP scheme with relay seal-in (Scheme 2)

Figures 8 and 9 also present the performance of the BFP scheme with relay seal-in. This scheme also performs satisfactorily in Case 1. In Case 2, the spurious BFI signal is sealed-in. As 50BF picks-up, this scheme operates and loses security.

3.3.3 BFP scheme to ensure timer turn-on (Scheme 3)

The performance of the BFP scheme ensuring timer turn-on is also represented by Figures 8 and 9. This scheme also performs satisfactorily in Case 1. In Case 2, the timer starts immediately on the reception of spurious BFI. At the end of the set timer value, the 50BF output will be high as the 50BF is set below the load current. This scheme also loses security and operates in non-fault situation. It has been observed that for a system with CIGs, the conventional practice of setting a low 50BF pickup for the BFP schemes will retain dependability but will lose security.

3.4 Impact of CIG on reset time of BFP

Upon clearance of a fault, the BFP scheme should reset. Subsidence current in CT results in a delayed reset of the BFP schemes. As a result, the BFP schemes lose security. To analyse this quantitatively, the subsidence phenomenon has to be comprehended. In this section, mathematical expression for the CT subsidence current is formulated using CT circuit model. Then, the impact of limited fault contribution of CIG on the CT subsidence current and hence on the reset time of BFP is investigated.
The equivalent circuit of CT used for the subsidence current modeling is shown in Figure 10. $L_m$ is the magnetising inductance, $R_s$ and $L_s$ are the leakage resistance and inductance of the secondary winding respectively and $R_l$ is the burden resistance. As mentioned in Section 2.3, subsidence current is a phenomenon observed in the secondary of the CT during a sudden interruption of the primary current. This occurs on account of the energy stored in the magnetisation branch that gets dissipated through the secondary resistance and the burden [24]. Figure 10 shows the current in the secondary circuit during uninterrupted current flow in the primary. The transformed primary current flowing in the secondary circuit is $I'_p$.

The equivalent impedance of the secondary circuit seen by $I'_p$ is given by

$$Z'_s = -\frac{X_m X_s}{(R_l + R_s)} + j\frac{X_m (R_l + R_s)}{(R_l + R_s)} + j\frac{X_s + X_m}{(R_l + R_s)},$$

(1)

where $jX_m$ is the magnetising branch reactance of CT and $jX_s$ is the secondary leakage reactance of the CT.

The secondary excitation voltage $V'_s$ is calculated as:

$$V'_s = I'_p Z'_s.$$  

(2)

Figure 12 shows the waveforms of $V'_s$ and $I'_p$ obtained from PSCAD simulation of the equivalent circuit of CT shown in Figure 10. The parameters used for simulation are given in Table A.1 of Appendix A. From these parameters, $Z'_s$ is calculated to be $3.31\angle 34.05^\circ \, \Omega$. From Figure 12, $I'_p$ is measured to be lagging $V'_s$ by $34.4^\circ$ during simulation. The small mismatch in the angles appears due to the numerical approximations. In Figure 12, when the primary current ceases to be zero, $V'_s$ retains a non-zero magnitude decided by $Z'_s$. Let the instantaneous value of $I'_p$ be $I'_p(t) = I_{pm} \sin(\omega t)$ and the secondary circuit equivalent impedance $Z'_s = |Z| \angle \theta$. Then, the instantaneous secondary excitation voltage is given by

$$v_s(t) = I_{pm} |Z| \sin(\omega t + \theta).$$

(3)

Assuming CB operation at zero crossing of primary current, this can be achieved at all odd and even integrals of $\pi$. At $\omega t = (2n + 1)\pi$, $r_s(t) = -I_{pm} |Z| \sin \theta$. At $\omega t = 2n\pi$, $r_s(t) = I_{pm} |Z| \sin \theta$.

At $t = t_i$, let the CB operate and the primary current gets interrupted, that is $i_p(t) = 0$. The secondary circuit reduces to a RL circuit that is shown in Figure 11. The energy stored in $L_m$ as well as $L_s$ gets dissipated in $R_l$ and $R_s$.

$$(R_s + R_l) i_s(t) + (L_s + L_m) \frac{di_s(t)}{dt} = 0.$$  

(4)
At $t = t_i$, let the secondary current be $i_s(t_i)$. The same current flows through the burden. Using Laplace Transform on (4), the subsidence current is calculated as

$$i_s(t) = i_s(t_i)e^{-\frac{E_{R}+E_{Ls}}{L_s+L_m}t}.$$  

The current $i_s(t_i)$ can be estimated from the magnitude of secondary excitation voltage $v_s(t)$ at $t = t_i$ and the magnetisation branch inductance $L_m$.

The time constant of decay of the subsidence current depends on the CT parameters. So for a given CT, the time taken by subsidence current to fall below a threshold will depend on the magnitude of the current flowing in the secondary during interruption. The fault contribution of CIG is significantly lower than the synchronous generator. As described before, the CT on the line emanating from CIG will see lesser fault current. As a result, CT subsidence current is expected to fall below the threshold faster. This is explained with an example in Figure 13. In Figure 13, CT subsidence current contributed by synchronous generator is compared with the CT subsidence current contributed by CIG. The CT secondary fault current is 100 A (20 p.u) for synchronous generator and 7.5 A (1.5 p.u) for CIG. The fault currents are interrupted at the zero crossing of the primary current waveform. In Figure 13(b), the CT subsidence current stays below the threshold value 3.75 A (0.75 p.u) in the case of CIG. The subsidence current in case of synchronous generator, however takes around 44 ms to fall below the threshold (Figure 13(a)). The BFP reset in case of synchronous generators gets delayed by around 2.75 cycles whereas it does not get delayed in case of CIGs. The effect of the subsidence current on the reset time of BFP schemes is therefore less significant for transmission lines emanating from CIGs.

4 PROPOSED ADAPTIVE 50BF SETTING

The fault current seen by the breaker on the transmission line emanating from CIG may be comparable with the load current due to the low fault contribution by CIG. As a result, it is difficult to differentiate fault situation from load situation using current values. Section 3.3 shows that the existing practice of low 50BF setting leads to loss of security of investigated BFP schemes. To address this issue, an adaptive setting of the 50BF pickup depending on the bus voltage is proposed here. During fault, the bus voltages drop significantly in presence of CIGs. The CIGs operate at the reduced voltages to fulfi the low voltage ride through requirement demanded by the grid codes. On the other hand, voltage stays around nominal value during non-fault situation. As a result, voltage information can be used additionally to differentiate load situation from fault situation.

During line to ground faults as well as line to line faults, the voltage magnitudes of the faulted phases drop. Hence, the phase
voltages $V_A$, $V_B$ and $V_C$ are used in the proposed method. In the proposed adaptive 50BF setting, the measured voltage of the faulted phase is first compared with a threshold. If this voltage is greater than the threshold, the 50BF setting is set at comparatively high value. This ensures security of the BFP scheme during loading situation. A voltage below the threshold indicates possible fault condition. The 50BF setting is set to a lower value if the voltage value is lower than the threshold. This ensures dependability during fault situation. The proposed adaptive 50BF setting is depicted in Figure 14. The adaptive 50BF setting $I_{set}$ is determined as follows.

$$V_{th} = V_{min} K.$$  \hspace{1cm} (6)

$$I_{set} = \begin{cases} I_{min}, & \text{if } V_b < V_{th} \\ I_{max}, & \text{if } V_b \geq V_{th} \end{cases}$$  \hspace{1cm} (7)

where $V_{th}$ is the threshold voltage, $V_{min}$ is the steady state under-voltage limit specified by the grid operator and $K$ is the safety margin coefficient whose value is lesser than unity. IEEE Standard C37.113-2015 [34] recommends that “the undervoltage setting should be lower than the lowest phase-to-neutral voltage under heavy power flow and depressed system voltage conditions”. $V_b$ is the bus voltage, $I_{min}$ and $I_{max}$ are the chosen 50BF settings. $I_{min}$ should be set below the minimum possible fault current seen by the breaker. $I_{max}$ should be set above the maximum possible load current seen by the breaker. The adaptive 50BF setting algorithm does not require any separate relay or additional infrastructure. The proposed adaptive 50BF setting algorithm should be incorporated in the existing BFP schemes. The proposed adaptive 50BF setting algorithm is summarised in a flowchart given in Figure 15.

5 | RESULTS

This section evaluates the performance of the proposed adaptive 50BF setting using PSCAD simulations. Impact of CIG
on the BFP reset time has also been analysed. The test system depicted in Figure 5 has been modeled in PSCAD. The test system has an operating frequency of 60 Hz. CIG2 at bus 2 has been modeled according to the parameters given in [28]. The voltage and current phasors have been estimated using Fourier full cycle algorithm. Sampling frequency of 3600 Hz has been used. The cut-off frequency of the anti-aliasing filter used has been set to 1200 Hz. The CT model used for BFP reset time study is shown in Figure 10. The parameters of the simulation models are presented in Table A.2 of Appendix A.

5.1 Performance of the proposed 50BF setting

The adaptive 50BF setting discussed in Section 4 is evaluated here. BFP for the circuit breaker CB25 located on the line emanating from CIG2 is investigated. The voltage of Bus 2 is used to change the 50BF setting adaptively. The bus voltage is compared with a threshold value of 0.7 p.u [34]. If the measured voltage drops below this threshold, 50BF is set at 0.75 p.u. If the bus voltage remains above 0.7 p.u, 50BF is set at 1.1 p.u considering maximum loading to be below 1.1 p.u. A fault (F1 in Figure 5) is initiated at time $t = 2$ s. Figure 16 presents the 50BF setting along with bus voltage. In Figure 16, the 50BF is set at 1.1 p.u during pre-fault situation. However, the 50BF setting is reduced to a low value (0.75 p.u) when bus voltage falls below 0.7 p.u during fault. Figure 17 shows the bus voltage waveform of the faulted phase. The lower setting of 50BF during fault ensures dependability of the BFP scheme. Figure 18 presents the corresponding BFI and BFP output signals.

Figures 19 and 20 correspond to situation when there is no fault. In this situation, the bus voltage remains above threshold value. As a result, the 50BF is set at a high value (1.1 p.u). As a result, the BFP will not operate even if there is spurious BFI signal. The higher setting of 50BF during loading situation ensures security of the BFP scheme. Figure 20 presents a spurious BFI during no fault and the BFP output signal.

5.1.1 Effect of fault resistance

The proposed adaptive 50BF setting depends on the bus voltage magnitude. The effect of fault resistance on the bus voltage during fault has been studied here. Figure 22 depicts the bus voltage behavior corresponding three different fault resistance values in the range 0–100 $\Omega$ for a fault at $t = 2$ s. It has been observed that for this practical range of fault resistance values, the bus voltage drops below the threshold value during fault. Hence, the proposed adaptive BFP scheme is not affected by fault resistance in this scenario.
5.2 BFP reset time in the presence of CIG

This section presents results to compare the BFP reset time when the fault is fed by CIG to that when a synchronous generator feeds the fault. A fault is initiated at time $t = 2$ s. The fault is successfully cleared by a CB in 3 cycles. Once the fault gets cleared, the CT subsidence current appears. The BFP is reset once the CT subsidence current falls below a threshold value. Figure 21 presents the BFP reset time when the fault is fed by a CIG along with the BFP reset time when the fault is fed by a synchronous generator. The CT subsidence current falls below the 50BF pickup threshold almost instantaneously with respect to breaker operation. As a result, BFP resets much faster in the case of CIG than synchronous generator. From Figure 21 it may be concluded that the reset of BFP is not delayed if the fault current seen by the breaker is low due to the presence of CIG.

6 DISCUSSIONS

This section discusses the impact of the proposed adaptive 50BF setting on the security and dependability of the BFP schemes.
In the existing BFP schemes, high dependability is achieved by setting the 50BF as low as 10% of nominal load current [23]. The requirement of such a low setting arises from the possibility of low current through the protected CB due to fault current distribution among breakers [24].

The proposed scheme considers the measured voltage as a parameter in deciding the pickup value. The pickup value is set at 10% only if the voltage drops below the threshold. Thus, the proposed 50BF setting helps in achieving the same high dependability as that of the existing schemes.

7 | CONCLUSION

Presence of CIGs poses significant challenges to the conventional protection schemes. This paper analyses the impact of CIGs on BFP which is an important backup protection scheme. Performance of three BFP schemes employed for transmission lines emanating from CIGs are investigated. It has been observed that the security of the BFP scheme with conventional 50BF setting deteriorates due to the limited fault current contribution by CIG. This paper proposes a current-based adaptive setting for 50BF element to enhance the security of BFP schemes while maintaining the dependability. The performance of the proposed 50BF setting has been analysed using PSCAD simulations. It is observed that, with the proposed 50BF setting, the BFP schemes perform satisfactorily in low fault current scenario. Also, in the presence of a spurious BFI signal, it is restrained from issuing the BFP trip signal in a no-fault situation. It has also been observed that for a practical range of fault resistance values, the proposed method performs satisfactorily. The results demonstrate that the proposed 50BF setting method achieves security for the BFP scheme without losing dependability. This paper also analyses the CT subsidence current in detail. Mathematical expression for subsidence current is derived from the CT equivalent circuit model. The impact of low fault contribution by CIG on BFP reset time has also been analysed. It is concluded that the reset of BFP scheme may not be delayed if the fault current seen by the breaker is low due to the presence of CIG. Analysis of the impact of CIGs on other types of backup protection schemes can be taken as future work.

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Nomenclature

- $L_m$: Magnetising inductance of CT
- $L_s$: Secondary leakage inductance of CT
- $R_s$: Secondary circuit resistance of CT
- $R_l$: Secondary burden resistance of CT
- $I_p$: Primary current of CT
- $i_p$: Instantaneous primary current of CT
- $I_{pm}$: Amplitude of $i'_p$
- $I'_p$: Primary current of the CT transformed to the secondary side
- $I_m$: Magnetising current of CT
- $i_p$: Instantaneous secondary current of CT
- $V_s$: Secondary excitation voltage of CT
- $v_s$: Instantaneous secondary excitation voltage of CT
- $V_o$: Voltage across the burden of CT
- $V_b$: Bus voltage magnitude
- $V_{th}$: Threshold voltage
- $V_{min}$: Steady state under-voltage limit
- $K$: Safety margin coefficient
- $I_{set}$: Setting for 50BF
- $I_{min}$: Low 50BF setting
- $I_{max}$: High 50BF setting

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APPENDIX A
The system parameters that have been used for PSCAD simulations are presented in this section.

A.1 CT equivalent circuit model
The parameters of the CT equivalent circuit model given in Figure 10 have been taken from [33].

A.2 Test system with synchronous generators and CIG used for testing BFP schemes
The parameters of the test system given in Figure 5 have been taken from [5]. The parameters for the CIG have been taken from [28].

TABLE A.1 CT circuit model parameters

| Parameter | Value |
|-----------|-------|
| R_s       | 2 Ω   |
| R_l       | 2 Ω   |
| L_m       | 0.157 H |
| L_s       | 0 H   |

TABLE A.2 Test system specifications

| Component   | Parameters       |
|-------------|------------------|
| SG1         | 230 kV, 60 Hz    |
|             | Z_{SG1} = 12.66∠83°Ω |
|             | Z_{SG1} = 11.1∠83°Ω |
| SG3         | 230 kV, 60 Hz    |
|             | Z_{SG3} = 7.76∠86°Ω |
|             | Z_{SG3} = 5.0∠86°Ω |
| SG4         | 230 kV, 60 Hz    |
|             | Z_{SG4} = 12.7∠82°Ω |
|             | Z_{SG4} = 11.2∠82°Ω |
| Reactor     | 75 MVAR          |
| Transmission line | Z_{L} = 0.0357 + j0.5077 Ω/km |
|             | Z_{L} = 0.3630 + j1.3262 Ω/km |
| Line length | Line 1–5 = 155 km |
|             | Line 2–5 = 100 km |
|             | Line 3–5 = 110 km |
|             | Line 4–5 = 120 km |
| CIG2        | 1.1 kV, 60 Hz    |
| PI block for current control | K_p = 1 |
| PI block for PWM generation | K_i = 1000 |

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