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Impact analysis of recovery ramp rate after momentary cessation in inverter-based distributed generators on power system transient stability

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Abstract
The global increase in the use of solar photovoltaics and wind turbines has led to a rapid increase in the penetration level of inverter-based distributed generators (IBDGs). Until recently, the operation modes of IBDGs under abnormal power system conditions were not a major concern owing to the small number of IBDGs used in power systems. However, several events have indicated that the momentary cessation (MC) mode of an IBDG can eventually deteriorate the stability of power systems. Among the various parameters that define the MC mode, the direct impact of the MC recovery ramp rate on the transient stability of the power system has been addressed by computing the stability margin based on a single machine equivalent method. Furthermore, this paper introduces the critical momentary cessation recovery ramp rate for a specific system, which can be used as an important index in the planning of an IBDG installation. Case studies on modified IEEE 39 bus system and Korean power system were conducted to validate the effectiveness of the proposed method.

1 INTRODUCTION

In recent years, the use of renewable energy sources (RESs), including solar photovoltaics (PVs) and wind turbines (WTs), has been rapidly increasing. Because most RESs are now connected to a bulk power system (BPS) through inverters at a low voltage level, power systems are confronting fundamental changes owing to the unique characteristics of an inverter, along with the variability and uncertainty of RESs [1, 2].

Various studies have investigated the impact of RESs on power system stability. Eftekharnejad et al. [3] addressed the impact of high penetration of PVs under both steady and transient state. The authors identified both the detrimental and beneficial impacts of PVs on transient stability. Kumar et al. [4] conducted a stability assessment of PV integration on a large power system. They analysed the transient and frequency stability under different PV penetration levels and dispatch strategies. Chowdhury et al. [5] analysed the impact of a doubly fed induction generator wind farm on the transient stability of a power system under several conditions. The simulation results showed that the transient stability deteriorates with increasing penetration of WTs. Shi et al. [6] assessed the effects of the wind power intermittency and volatility on the transient stability in terms of the critical clearing time and angle-based margin index. The variation in wind power and its effect was demonstrated through a Monte-Carlo simulation. Although the impact of RESs on the power system stability was studied from various perspectives, until recently, the impact of the unique operation modes of inverter-based distributed generators (IBDGs) under abnormal power system conditions had not been investigated.

When a BPS is experiencing abnormal conditions, an IBDG operation can be categorised into four different modes [8], among which the momentary cessation (MC) mode has been one of the major topics of concern since its impact on power system stability has been clarified through several events. In particular, in 2016 and 2017, two major events occurred that evoked the importance of analysing the effect of MC during a power system operation. The Blue Cut Fire, which occurred on 16 August 2016, was initiated by a 500 kV line-to-line fault near Lugo-substation, eventually resulting in the widespread...
loss of 1,200 MW PV plants [9]. On 9 October 2017, the occurrence of the Canyon 2 Fire resulted in the widespread reduction of 900 MW PV facilities [10]. In both events, the main reason for the loss was found to be the MC mode of the PV inverters. These two events demonstrated that the MC mode of an IBDG may deteriorate the transient stability, particularly when the renewable penetration level is high. After the occurrence of several events indicating negative effects of the MC mode, the North America Electric Reliability Corporation (NERC) organised its inverter-based resources performance task force (IRPTF) to conduct a detailed analyses and provide performance recommendations to mitigate the negative effects of IBDGs on a BPS. The NERC IRPTF suggested the following recommendations to the power industry to change the parameters to minimise the MC operation of an IBDG. They recommended to reduce the recovery delay time into one to three cycles, ensure a power ramping capability of 1 pu/s following the MC mode and ensure a lower MC threshold voltage [11].

As such, a few studies have evaluated the impact of the MC mode on power systems. Choi et al. [13] investigated the relationship between the MC threshold voltage and the short circuit current. Zhu et al. [14] addressed the impact of the MC mode and its recovery delay on the transient stability. Shin et al. [15] analysed the impact of the MC threshold voltage on the power system transient stability. In addition, the authors addressed the direct impact of the MC mode on the stability margin and conducted a simulation on a Korean power system. Shin et al. [29] analysed the impact of MC mode in high-generation areas while considering the special protection schemes (SPS) such as tripping of generators. Here, high-generation area refers to area where significant amount of generation is concentrated. The study illustrated that in high-generation area, generator tripping and MC mode in IBDGs may impact power system positively in terms of transient stability. However, though MC in IBDG and SPS of generator ensures transient stability, negative impacts on frequency stability may arise with lower frequency nadir and steeper rate of change of frequency. Pierre et al. [16] analysed the control models of inverters, including the MC mode. The impact of various parameters, such as the system reserve, control droop, and time constant, on the power system frequency was addressed. However, although the ramping capability is one of the major parameters in the MC mode as pointed out by NERC IRPTF, no studies have addressed its impact on the transient stability of a power system.

The recovery ramp rate in a transient time frame can potentially impact the power system stability [17, 18]. However, among the major MC mode parameters, the recovery ramp rate is a parameter with no clear consensus on its criteria. The IEEE 1547, revised in 2018, recommends a ramping capability of 2 pu/s for the first 0.4 s immediately after an IBDG starts the recovery process when a threshold voltage setting of 0.5 pu is applied [8]. In contrast, California Independent System Operator (CAISO) proposes that IBDGs be given the ability to return to their original output with a ramp rate of 1 pu/s along with an MC threshold voltage of 0.5 pu [12], which is identical to the recommendation [11].

Although previous studies have analysed the impacts of IBDG on power system stability and demonstrated the impacts of the MC mode [3–6, 13–16, 29], no research has investigated the impacts of recovery ramp rate after MC. The main contributions of this paper are as follows:

- This study investigates the direct impact of the recovery ramp rate after MC mode on power system transient stability with single machine equivalent (SIME) method.
- Furthermore, this paper proposes a minimum recovery ramp rate for IBDG to secure transient stability of a power system.

The remainder of this paper is arranged as follows. Section 2 describes operation modes of the IBDG and its momentary cessation mode. In Section 3, the impact of the recovery ramp rate after MC mode on the transient stability is analysed using the SIME approach. Finally, in Section 4, the method for determining the critical MC recovery ramp rate is simulated on a Korean power system.

2 | OPERATION MODES OF IBDG AND KEY FEATURES FOR MC ANALYSIS

During abnormal conditions, an IBDG can operate under four different operation modes according to the voltage conditions: continuous operation (CO), mandatory operation (MO), MC, and trip modes. Figure 1 illustrates each operation mode in detail [8]. In the CO mode, an IBDG is connected to a BPS and injects power to the system. The CO mode corresponds to a normal voltage range of 0.88–1.1 pu. The MO mode is defined for an abnormal voltage condition of 0.5–0.88 pu; in this mode, the IBDG still exchanges power with the connected system and retains synchronism. However, if the IBDG enters the MC mode, which is defined for voltage ranges of 0–0.5 and 1.1–1.2 pu, despite being connected to a bulk power system, no active current injection nor reactive power exchange occurs [33].

![FIGURE 1 Operation modes of inverter-based distributed generator (IBDG) according to voltage level](image-url)
This operation scheme is expressed as ‘cease to energise’ [8] or ‘power electronic firing commands are blocked’ [22].

The MC mode was originally designed to protect the distribution system by limiting the contribution of IBDGs on the fault current. Until recently, owing to the low penetration level of IBDGs, an MC-related stability issue was not a major concern in a power system. However, following a few MC-related events, the analysis of the impacts of MC mode on a power system became necessary, with NERC publishing modelling guidelines for IBDGs [22]. The guidelines address several functions that should be contained in an IBDG model for an appropriate MC representation at the system level. According to the guidelines, the low/high voltage threshold of the MC, recovery delay, and active/reactive current recovery ramp rate are key features that must be represented in the IBDG model to determine the MC operation, as depicted in Figure 2. Recovery ramp rate after the MC mode is defined as the rate of recovery in active current on the assumption that IBDG only injects active power to BPS.

### 3 IMPACT OF RECOVERY RAMP RATE AFTER MOMENTARY CESSATION ON TRANSIENT STABILITY

A one machine infinite bus (OMIB) configuration with a SIME approach is a conventional method to assess the transient stability of a complicated power system. This section discusses how the SIME approach was utilised to analyse the effect of the recovery ramp rate on the transient stability of the power system.

#### 3.1 Current injection model for SIME-based transient stability assessment

To address the impact of the recovery ramp rate after the MC mode on the transient stability by applying the SIME approach based on an OMIB configuration, an IBDG is represented as a simple current-injection model with a parallel impedance as depicted in Figure 3. When the parallel impedance is assigned a zero or is short-circuited, IBDG can be analysed as in the trip or MC mode. By contrast, if a parallel impedance is assigned as a rated value, IBDG injects its rated power into a bulk power system. During the recovery period after MC mode, the parallel impedance is increased to its rated impedance from zero. By assigning an appropriate impedance, the simple current injection model depicted in Figure 3 can represent the various states of IBDGs in terms of power injection. This time-varying parallel impedance during the recovery period can be further used as a major parameter when configuring the OMIB system with IBDGs and analysing the impact of the recovery ramp rate on transient stability.

#### 3.2 Impact of recovery ramp rate on transient stability with SIME configuration

This section presents the derivation of an OMIB configuration with the SIME approach to address the impact of the recovery ramp rate on the transient stability. Then, the effect of the recovery ramp rate is analysed based on the designed OMIB configuration.

The SIME method is a hybrid or temporal-direct method that can be used to evaluate the power system stability because the SIME utilises a direct transient stability method with equal area criterion based on a time-domain simulation [19–21, 30–32]. SIME demonstrates loss of synchronism by dividing the generators into two groups: critical and non-critical generator groups, using a short dynamic simulation. Subsequently, based on the information obtained from the two generator groups, the OMIB system that computes the stability margin is developed as follows:

\[
\delta_{C}(t) = \sum_{k \in C} \frac{M_k \delta_k}{M_C},
\]
The impedance of the equivalent machine, $Z_T$, can be expressed as a parallel connection of non-critical generators, loads and IBDGs. Thus, the impact of the recovery ramp rate after MC mode on critical generators is represented as a change in $Z_T$. In contrast, $Z_C$ and $Z_{TL}$, each corresponding to the equivalent impedance of critical generators and transmission lines, are not affected by the MC mode [15, 29]. As previously demonstrated, if the recovery ramp rate is considered, the parallel impedance of the current-injection model varies over time. This time-varying equivalent impedance of an IBDG seen from critical generator is reflected into the OMIB configuration using the SIME method. When the recovery speed is limited to a small value, the equivalent reactance of the IBDG changes slowly, and thus, $Z_T$ decreases slower compared to fast recovery case. Thus, if IBDGs recover slowly after MC mode, slow decrease in $Z_T$ limits increase in $P_e$ during the recovery period. Eventually, a slow change in the equivalent reactance deteriorates the transient stability by limiting the deceleration area, as depicted in Figure 5. In the SIME-based configuration, this reduction by recovery ramp rate can be expressed as (7) because the impacts of recovery ramp rate are limited to an electrical power reduction immediately after a fault and are not closely related to the inertia constant of conventional generators. Here, $P_{edd}(t)$ was applied to represent this electrical power reduction after a fault clearing. Because the impact of the critical generator group is greater than that of the non-critical generator group in constructing the OMIB configuration, $P_{edd}(t)$ can be viewed as having an effect on the critical generator groups. As this study is focused on the transient time frame, during the analysis, the mechanical power is assumed to remain constant:

$$P_e(t) = \frac{M_C M_N}{M_C + M_N} \left( \sum_{i \in EC} P_{edd}(t) - \sum_{i \in N} P_{ei}(t) \right).$$

(7)
A reduction in the deceleration area will increase as the IBDG recovers slower to its original output. Eventually, the slow recovery after the MC mode may lead the generators to lose their synchronism. This implies that the fast recovery capability can contribute to the transient stability of power system by preventing unintended reduction in the deceleration area. At the same time, a minimum ramp rate to secure transient stability can be assessed for a power system according to each system condition. Thus, the critical recovery ramp rate of an IBDG is introduced for the secure operation of a power system.

3.3 Critical momentary cessation recovery ramp rate

As introduced in the previous section, the transient stability margin differs according to the recovery ramp rate. Slow recovery of an IBDG after the MC mode deteriorates the transient stability. Hence, the minimum recovery ramp rate after the MC, ensuring transient stability, should be assessed for the secure operation of a power system. This minimum recovery ramp rate cessation is defined as a critical momentary cessation recovery ramp rate (CMCR). The CMCR of a specific system can be determined by computing the critical recovery ramp rate for each contingency and extracting the largest value. Note that the critical recovery ramp rate of each contingency is defined as a recovery ramp rate when acceleration area and deceleration area gets equal for the applied contingency. Figure 6 shows the flowchart for CMCR evaluation. Based on the defined contingency sets, a short time-domain simulation is conducted to configure the OMIB system, after which the critical recovery ramp rate of each contingency can be defined. If the computed critical ramp rate of contingency is high, the applied contingency can be evaluated as a severe contingency. Among the calculated critical recovery ramp rates, the maximum recovery ramp rate can be called as the CMCR of the system for study. A specific system can prevent an MC-related transient instability issue by enforcing the IBDGs to ensure a ramping capability greater than the CMCR.

4 SIMULATION STUDY

4.1 Case study on modified IEEE 39 bus system

The impact of recovery ramp rate following the MC mode is simulated and analysed on modified IEEE 39 bus system which is well known as 10-machine New England power system. The modification on IEEE 39 bus system was done by substituting 25% of total generation with IBDGs at 10 different locations as depicted in Figure 7. By substituting 25% of total generation with IBDGs, each generator output was reduced by 25% compared to its original electrical output. The data on load and generation are illustrated in Tables 1 and 2. Specific parameters of generators and transmission lines remain unchanged except for the electrical output of the generators [34, 35]. For the represen-
Table 1 Inverter-based distributed generator (IBDGs) in modified IEEE 39 bus system

| Location | Installed capacity (MW) | Location | Installed capacity (MW) |
|----------|-------------------------|----------|-------------------------|
| Bus 4    | 250                     | Bus 3    | 50                      |
| Bus 5    | 250                     | Bus 15   | 50                      |
| Bus 7    | 250                     | Bus 16   | 50                      |
| Bus 8    | 250                     | Bus 18   | 50                      |
| Bus 11   | 250                     | Bus 27   | 50                      |
| Total    | 1500 MW                 |          |                         |

Table 2 Load share in modified IEEE 39 bus system

| Generator type | Generation (MW) | Ratio (%) |
|----------------|-----------------|-----------|
| Conventional generator (G1–G10) | 4392       | 74.54     |
| IBDG            | 1500           | 25.46     |
| Total           | 5892           | 100       |

The contingency scenario applied to the modified IEEE 39 bus system is as follows. The three phase to ground fault occurs on a transmission line, which connects bus 10 and bus 13, near bus 10 when simulation time reaches 1 s. After 200 ms, fault is assumed to be cleared with the trip of transmission line. For the applied contingency scenario, the critical generator was found to be the G3 which is connected to bus 32.

To illustrate the impact of recovery ramp rate, simulation on modified IEEE 39 bus system was conducted for three different recovery speeds. During the fault, as recovery ramp rate has its impact after the fault clearance, response of IBDGs and critical generator remains same. However, when simulation time reaches 1.2 s and fault is cleared through the line trip, response of IBDGs varies significantly according to recovery ramp rate as depicted in Figure 8, and has great transient impact on critical generator as illustrated in Figure 9(a) and (b). Figure 8 depicts the recovery of $d$-axis current of an IBDG connected to bus 4 after the MC mode, which applies same for the IBDGs that entered the MC mode. In Table 3, electrical output of a critical generator is illustrated when return angle for each recovery speed is captured. When simulation time reaches 1.621 s and return angle of simulation case with recovery speed of 2.0 pu/s is captured, electrical output reduction of 56.42 MW and 99.22 MW arise according to recovery ramp rate compared to fast recovery case with recovery ramp rate of 2.0 pu/s. Note that the ‘return angle’ is defined as the maximum angle during the time-domain simulation for a stable system which is marked as a red dot. Figure 9 and Table 3 show that slow recovery of IBDG after the MC mode results in electrical output reduction of critical generator. If not sufficient recovery speed is guaranteed, electrical power reduction of critical generator increases significantly and may eventually leads critical generator to lose synchronism by limiting deceleration area.

Then, critical recovery ramp rate for the applied contingency scenario is evaluated. Figure 10(a) illustrates the change in power–angle curve according to recovery ramp rate which can be directly used for transient stability assessment while Figure 10(b) depicts change in rotor angle of critical generator. It shows that the recovery ramp rate smaller than 0.57 pu/s leads critical generator to lose synchronism by limiting deceleration area and thus, critical recovery ramp rate for the applied contingency can be determined as 0.57 pu/s.

4.2 Case study on Korean power system

The proposed method for evaluating the CMCR of the specific system was applied to a Korean power system. The government of Korea recently planned to increase the installation capacity of its IBDGs (with a specific aim to increase the penetration level of the PVs and WTs) up to 58.5 GW until 2030 and supply 20% of the total load [24, 25]. Owing to its high solar irradiance and large plains available for PV use, the Honam area is expected be installed with a large portion of the new IBDGs, approximately 17.2 GW by 2030, as described in Table 4 [26, 27]. Based on this plan, by 2022, the IBDGs installed in Korea will reach a total generation of 23.3 GW, and the Honam area is expected to hold approximately 30–35% of the total number of IBDGs. Thus, the peak generation of IBDGs in the Honam area by 2022 is likely to reach 8 GW.
FIGURE 9  Simulation results of modified IEEE 39 bus system. (a) Electrical output of critical generator; (b) rotor angle of critical generator

Considering the worst-case scenario, the simulation case was assumed to be conducted during the peak IBDG generation period. The total generation of the IBDGs in the Honam area is set to 8 GW, and the power output of conventional generators was adjusted according to their merit order. In Honam area, 24 power plants generating approximately 8.9 GW including 6 nuclear power plants generating 6.1 GW are in service during the peak generation period. The specific IBDG distribution status is described in Table 5. All IBDGs were connected to 22.9 kV buses and assumed to operate at unity power factor with specific parameters according to reference [15].

The fault scenario applied to each contingency set is as follows. Three phase faults were applied to the predefined

FIGURE 10  Response of critical generator according to different recovery ramp rates. (a) Power-angle curves; (b) rotor angle trajectories

TABLE 4  Renewable energy source (RES) plan of Korea and portion of Honam area

| Year | Korea (GW) | Honam area (GW) | IBDG share of Honam (%) |
|------|------------|-----------------|------------------------|
| 2018 | 11.6       | 3.6             | 31.12                  |
| 2030 | 58.5       | 20.8            | 35.56                  |

TABLE 5  Installed capacity of inverter-based distributed generator (IBDG) in Honam area

| Area            | Installed capacity (GW) | Percentage (%) |
|-----------------|-------------------------|----------------|
| Gunsan area     | 2.08                    | 26.00          |
| Shinwhasun area | 2.37                    | 29.62          |
| Shingangjin area| 1.31                    | 16.38          |
| Gwangyang area  | 0.90                    | 11.25          |
| Rest of Honam   | 1.34                    | 16.75          |
| Total           | 8.00                    | 100            |
contingency line when the simulation time reaches 1 s. This fault is assumed to be cleared normally after six cycles (0.1 s) with a line trip. All major contingencies that can affect the Honam area are defined as a contingency set to compute the critical recovery ramp rate. As the transmission system of the Honam area has three voltage levels of 22.9, 154, and 345 kV, the major contingency sets are defined as double faults of 345 kV transmission lines except for the lines directly connected to the generators.

Figure 11 shows the impacts of recovery ramp rate on critical generators and deceleration area. As previously demonstrated, the simulation results showed a decrease in the deceleration area under a slow recovery. If a sufficient recovery speed is not guaranteed, the return angle does not exist, and the critical generator loses synchronism with the power system. In the case of the ‘Shinnamwon-Shingwangju’ contingency, a recovery ramp rate of at least 1.05 pu/s should be applied to prevent transient instability by applying the MC mode. If a recovery ramp rate of below 1.05 pu/s is applied, the critical generators lose synchronism and the return angle is not shown. Figure 12 illustrates the simulation results for the “Shinnamwon-Shingwangyang” contingency, which was found to be the second-worst contingency case. The critical recovery ramp rate for this contingency was found to be 0.99 pu/s. Starting from the second-worst contingency with the second-largest critical recovery ramp rate, the simulation results of the remaining contingency sets do not contribute to adjusting the recovery ramp rate because the CMCR is determined to be the maximum value among the computed critical ramp rates. Furthermore, as recommendation on recovery ramp rate is already larger than 0.99 pu/s, critical recovery ramp rate from ‘Shinnamwon-Shingwangyang’ contingency does not
contribute in adjusting the required recovery ramp rate [11, 12]. The detailed simulation results including the return angles and critical generators are presented in Table 6.

In this case study on Korean power system, the CMCR was found to be 1.05 pu/s. The simulation results imply that the 1 pu/s recommendation in references [11, 12] may be insufficient for the secure operation of a power system when IBDG penetration reaches high. Hence, studies should be conducted to determine the required recovery ramp rate before IBDG penetration level peaks high in a specific power system.

5 | CONCLUSION

This study examined the impact of the recovery ramp rate following the MC operation mode on the transient stability of a power system. The study was conducted based on the stability margin computed using the SIME-based OMIB configuration. Furthermore, CMCR is proposed as a minimum recovery ramp rate to secure transient stability of a power system. A case study was then conducted on a Korean power system to validate the effectiveness of proposed method. The main contributions and conclusions drawn are as follows:

- Impact of recovery ramp rate after MC mode on transient stability is analysed with SIME method.
- The slow recovery of the IBDGs following the MC mode eventually deteriorated the transient stability by limiting the deceleration area during the post-fault period.
- This paper proposes a CMCR, which is defined as the minimum recovery ramp rate that IBDGs need to ensure to avoid transient instability.
- Simulation results from modified IEEE 39 bus system and Korean power system showed that slow recovery of IBDG after MC mode deteriorates transient stability as analysed.
- CMCR captured from case study implied the necessity of faster recovery than current standards may arise when IBDG penetration level reaches high.

The proposed method of determining CMCR may require a long computation time because all major contingencies must be screened to extract the maximum value and determine the CMCR of the system. Additionally, because CMCR is dependent on the simulation case, a power system operator should repeat the overall computation to update CMCR. Nevertheless, the proposed method and CMCR can be used as a major index in the power system planning procedure.

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