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Potential Impacts of Misconfiguration of Inverter-Based Frequency Control

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***Abstract*—This paper focuses on a transmission system with a high penetration of converter-interfaced generators participating in its primary frequency regulation. In particular, the effects on system stability of widespread misconfiguration of frequency regulation schemes are considered. Failures in three separate primary frequency control schemes are analyzed by means of time domain simulations where control action was inverted by, for example, negating controller gain. The results indicate that in all cases the frequency response of the system is greatly deteriorated and, in multiple scenarios, the system loses synchronism. It is also shown that including limits to the control action can mitigate the deleterious effects of inverted control configurations.**

***Index Terms*—communication latencies, configuration failure, droop, photovoltaics, primary frequency control, smart grid, synthetic inertia**

I. Introduction

Today's grid is being reshaped by the massive installation of converter-interfaced devices both at the generator and load sides of the system [1]. This technology allows for more controllability in the consumption of power as well as its production. At the same time, new monitoring devices such as smart meters, digital fault recorders and phasor measurement units (PMU) are changing the way that data is captured and analyzed in power systems. Most of the time these new technologies have the ability to communicate measurements or status data and receive commands over a network.

These changes are creating opportunities for a more flexible and reliable grid. For instance, it has been shown that the controllability of distributed energy resources coupled with the availability of remote measurements can improve the power quality of distribution feeders [2], [3]. The Smart Inverter Working Group (SIWG) has created a list of communications-based grid support functionality for inclusion in the CPUC Electric Rule 21 [4]. This document covers requirements for monitoring data, and the control parameters for ramp rate, curtailment, frequency-watt, volt-watt, reactive power support, and other grid functions. Research in the bulk power system has proposed control schemes to improve power system frequency regulation in the presence of high penetration of converter-interfaced generators (CIGs). Specifically, it has been shown that using average system frequency instead of local measurements improves the droop and synthetic inertia control strategies [5], [6]. A method that uses communication and CIGs in a feed-forward control scheme to correct power imbalances is proposed in [7]. While communicating information and networked grid devices have multiple benefits, there are also some disadvantages and potential risks. Drawbacks such as delays and the possibility of interruptions have been successfully addressed for the control methods proposed in [2], [3], [5]–[7].

This paper considers the scenario where a significant portion of a power system's generation, provided by networked CIGs, experience a widespread configuration failure. The CIGs are providing frequency regulation support to the system and the malfunction considered inverts their control action by negating certain parameters intended to be non-negative. (The effects of unstable high gain configurations are covered in [5]–[7].) The CIG control schemes analyzed, separately, are droop control [5], synthetic inertia [6], and feed-forward compensation [7]. Time domain simulations were performed for the three control schemes with different settings. The results of these simulations show that the system with corrupted control may lose synchronism following a disturbance even for cases where the negative gains are small. This paper also shows that imposing limits on the amount of active power provided by each CIG is effective in preventing the system from losing synchronism in these scenarios.

II. Background and Study Results

CIGs have been demonstrated to be effective in providing frequency regulation support to the system. With the proper tuning of control parameters these devices can even improve the frequency response of the system [5]–[7]. This section analyzes the effects on the frequency response of the system following a power imbalance event when these parameters are corrupted.

The test system used in this work is a reduced model of the US Northeast Power Coordinating Council (NPCC) region with 140 buses and 48 generating units. In this model, roughly 50% of the total generation (26 generators) was converted to CIG. The event considered is the loss of a unit, in the Midwest region, producing 655 MW or nearly 2.3% of the

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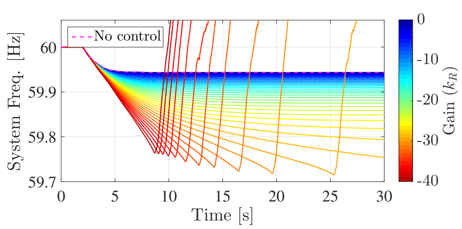
total power in the system. The CIG models installed in the system correspond to a custom model of a controlled current injection representative of the power electronics interface of both PV plants and Type-4 WTGs [5], [6]. The simulations of this paper were performed in the GE developed power system dynamics simulation package, PSLF.

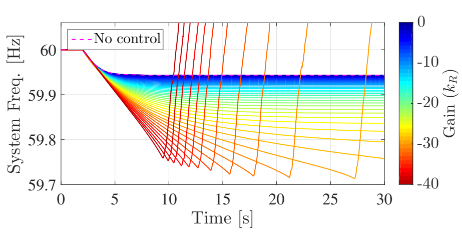
A. Frequency Droop

Similarly as in conventional generators, droop control in CIGs consists of a proportional control action where the device adjusts its power levels according to frequency deviations [8]. This type of control is similar to bi-directional frequency-watt functions [9]. Typically, the droop control feedback signal is the local frequency at the bus to which the CIG is connected. However, it has been shown that improvements in the control action can be achieved if this feedback signal is a system (average) frequency; this approach is termed CE-Droop. This section studies the effects on the initial frequency response of the system when the droop control action provided by CIGs is misconfigured and the control action is inverted. In this scenario, which is achieved by using a negative droop gain or inverting the frequency-watt function, CIGs will decrease their power output when the frequency drops exacerbating the initial power imbalance. Note that in the scenarios considered in this paper, it is assumed that all the CIGs in the system are affected by the parameter misconfiguration. This corresponds to the worst-case scenario from that perspective and gives more information about the extent of deterioration of the system.

Fig. 1 shows the frequency response of the system for the loss of generation event described above when the proportional gain of the CIGs included in the system has different negative values ranging from -1 to -40. Fig. 1a shows the results when the CIGs control action is the traditional droop (for reference, a typical value for frequency droop for conventional generation is 5%, or $k_R = 20$ [10].) These results show that the drop in system frequency is exacerbated by the CIG action, as anticipated. With negative values of droop gain of -25 and beyond, the system loses synchronism which is observed in Fig. 1a as the average frequency spirals out of control. Note that for these cases the time it takes the system to go unstable decreases as the negative gain increases. Fig. 1b shows the results for the CE-droop case, where the feedback signal of the CIGs is the system (average) frequency without any latency. These results show the same behavior as those in Fig. 1a with the system losing synchronism for negative gains of -25 and higher (in magnitude).



(a) Conventional droop.



(b) CE droop.

Fig. 1: System frequency response for the loss of generation event. Top figure: conventional droop. Bottom figure: CE-Droop.

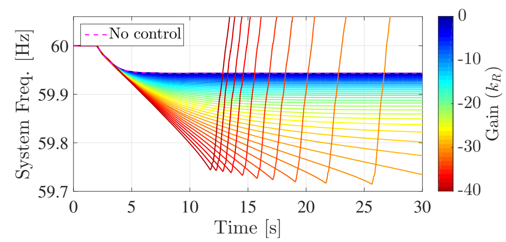


Fig. 2: System frequency response for different inertial gain values when the CIGs have CE-Droop control with a 500 ms delay.

Fig. 2 shows the frequency response of the system for an additional case of study when the feedback signal for the CE-Droop scheme has a delay of 500 ms. The results for this case are similar to those in Fig. 1 in terms of the magnitudes of the negative gain that cause the system to lose synchronism. However, it can be observed that the time the system take to become unstable is increased considerably. For instance, while for a gain of $k_R = -40$ the system loses synchronism at around 9 s for CE-FAIR with no delay in Fig. 1b, the same effect is reached after 13 s for the case of 500 ms delay in the feedback signal.

B. Synthetic Inertia

Synthetic inertia enables CIGs to participate in the primary frequency response by emulating the inertial response of traditional generators. The active power output of the CIG is proportionally adjusted in response to the measured frequency derivative.

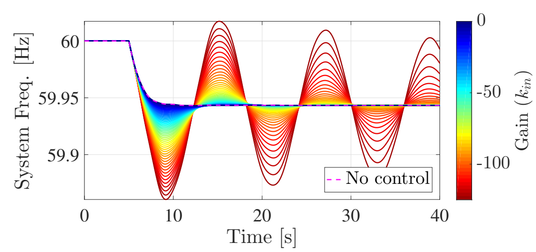


Fig. 3: System frequency response with synthetic inertia.

Fig. 3 shows the system frequency response with synthetic inertia deployed having different inertial gain (k_{in}) values in the range of 0 to -125; simulation results indicated loss of synchronism with gain beyond -125. For reference, this is equivalent to an inertia constant of 0 to 3.75 s; thermal and hydraulic units typically have inertia constants in the 2 to 10.0 s range [10]. Comparing to the case without any feedback controls enabled, the negative gain values adversely affect the system response, more so as the magnitude of the gain increases. However, the system does remain robust against this type of parameter adjustment within this range of gains. If controller gain were aggressively tuned to higher values for a stronger response, then negation of the controller gain could lead to instabilities after system disturbances.

Communication-enabled synthetic inertia (CE-SI) was found to have promise in improving the system inertial response [6]. This variation on synthetic inertia uses a system-averaged frequency for its control law. This system frequency must be computed using communicated information and introduces potential latency in control action.

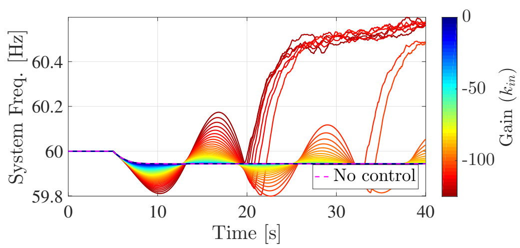


Fig. 4: System frequency response with CE-SI using different controller gains.

Fig. 4 shows how the system response changes with CE-SI deployed instead. Note that the range of stable gains for CE-SI is slightly smaller than that of SI. Fig. 5 shows the results for 500 ms of communication latency is considered; the delay can be observed by the shifted frequency nadir locations. Contrary to intended performance, the introduction of communication latency increases system robustness to parameter adjustment, allowing for higher magnitude controller gain before experiencing instability.

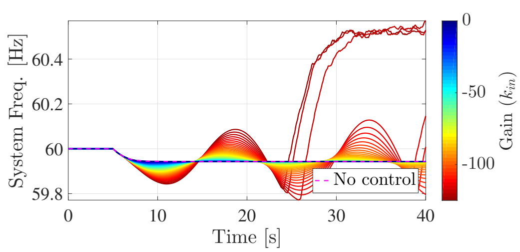


Fig. 5: System frequency response with CE-SI and 500 ms of communication latency.

C. *Feedforward control: Communication-Enabled Fast-Acting Imbalance Reserve*

CIGs can also provide frequency regulation using a feedforward control strategy named Communication-Enabled Fast-Acting Imbalance Reserve (CE-FAIR) [7]. In this approach, participating CIGs are redispatched to correct the power imbalance. The CIG redispatch and identification of power imbalances occurs through communication networks and are also subject to latency. If the power imbalance is misidentified or the command order to the CIGs is inverted, the CE-FAIR action may act to further increase, rather than reduce, the power imbalance. Note that in CE-FAIR, the amount of the power imbalance to be provided by CIGs is determined by a parameter, η, known as the power compensation level.

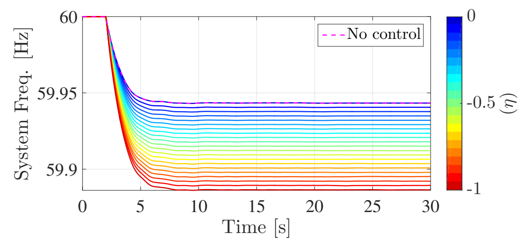


Fig. 6: System frequency response for different power compensation level values.

Fig. 6 shows the frequency response of the system for the loss of generation event for cases when η ranges from 0 to -1.When η is zero, no control action is performed. When η is -1, CIGs reduce their power to match the original generation drop and the total drop experienced by the system is double the original. These results show that the frequency of the system experiences a much larger drop and both the settling frequency and the frequency nadir of the system are reduced with respect to the no control case. Even though the overall response of the system is affected, the system does not lose synchronism even for the worst case of $\eta = -1$. This contrasts with the results outlined in the two previous sections where the controls acting contrary to their intended action are capable of making the system lose synchronism. The two previous control strategies are based on feedback control which can create positive feedback if poorly configured, enabling even small disturbances to drive the system unstable. CE-FAIR, being a feedforward control action, does not allow for that same possibility and is therefore less deleterious to the system when its parameters are misconfigured.

Because CE-FAIR relies on communications, it is reasonable to expect that its action is subject to a certain latency. The effects of this latency when the control CE-FAIR control action is harmful to the system are presented in Fig. 7. In these results, the power compensation level was set to -1. The results in Fig. 7 show that because the control action is delayed, the initial change in the frequency is not increased and the initial negative effect of the CE-FAIR action on the rate of change

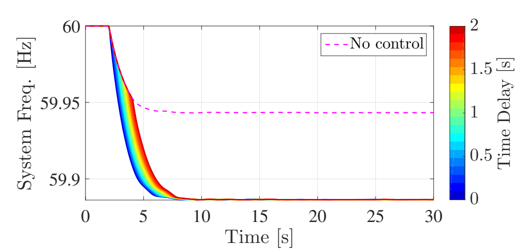


Fig. 7: System frequency response when $\eta = -1$ for different cases of delay in the control action.

of frequency is reduced.

III. Bounded active power modulation

One possible solution to mitigate the described type of parameter misconfiguration is to impose limits on the amount of active power permitted to be modulated by the CIG controllers. These limits may be implemented by hardware solutions or firmware solutions less susceptible to, e.g., operator or device error. This section shows how bounding the modulation of active power mitigates the pernicious effects to the grid of destabilizing CIG control actions, specifically the feedback control schemes of frequency droop and synthetic inertia. To analyze the effect that limits on the control actions have on the overall stability of the system, simulations for these control strategies were performed. In these simulations, the limit to which each CIG is allowed to vary from its power level is adjusted from 0 to 30% in steps of 0.5%. This limit is noted as ΔP_{lim} and for a single CIG can be represented by,

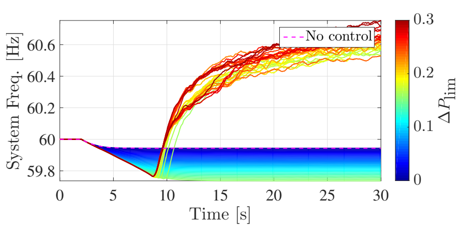
$$P_{\text{max}} = P_{\text{sched}}(1 + \Delta P_{\text{lim}}) \tag{1}$$

$$P_{\text{min}} = P_{\text{sched}}(1 - \Delta P_{\text{lim}}) \tag{2}$$

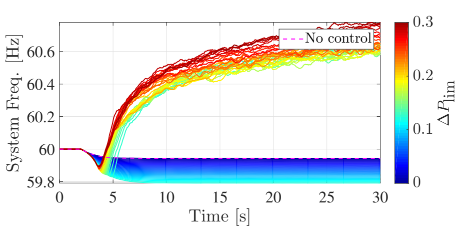
where P_{sched} is the scheduled output power of the CIG. Note that when ΔP_{lim} is zero, no control action is permitted.

A. Frequency droop

The system response to the tripping generator event when the control action of the CIGs is conventional droop for different values of ΔP_{lim} is presented in Fig. 8. The results for negative gains of $k_R = -40$ and $k_R = -100$ are presented in Figs. 8a, and 8b, respectively. Note that these gains are both unstable according to Fig. 1a. The results in Fig. 8 show that limits in the CIG modulation of active power can prevent the system from losing synchronism. It can be observed that when $k_R = -40$ then ΔP_{lim} can be as high as 15% before the system stability is compromised, and that this value drops to 12% for the case of $k_R = -100$.



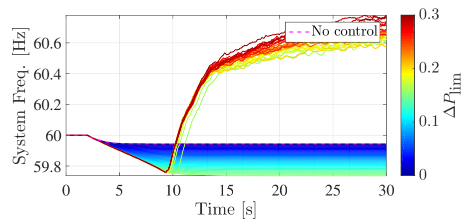
(a) $k_R = -40$.



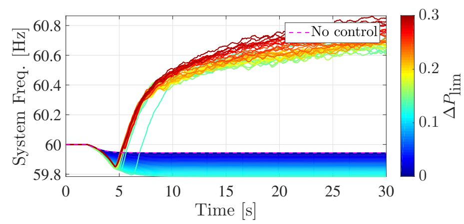
(b) $k_R = -100$.

Fig. 8: System frequency response for the loss of generation event. The control action is conventional droop control and the gains considered are $k_R = -40$ (top) and $k_R = -100$ (bottom).

The same study on how ΔP_{lim} affects the stability of the system when the control action for the CIGs is CE-Droop (and this action is corrupted) is presented in Fig. 9. The gains for the control action are again selected to be $k_R = -40$ and $k_R = -100$ and the results of the frequency response of the system following the loss of generation event are presented in Figs. 9a and 9b, respectively. Figs. 9 show a comparable result to those in Fig. 9 where limits of ΔP_{lim} up to 12% and 15% are able to prevent the negative feedback action of the CIG controllers from destabilizing the system.



(a) $k_R = -40$.



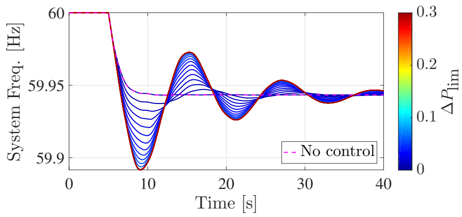
(b) $k_R = -100$.

Fig. 9: System frequency response for the loss of generation event. The control action is CE-Droop and the gains considered are $k_R = -40$ (top) and $k_R = -100$ (bottom).

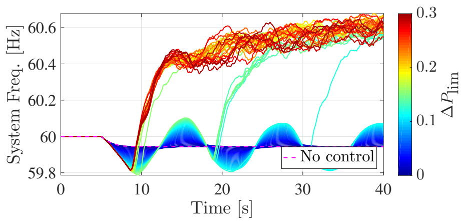
B. Synthetic inertia

Fig. 10 shows the impact of employing an active power modulation limit on synthetic inertia. In Fig. 10a, k_{in} is set to -100, well within the range of stable negative gain values. As a result, ΔP_{lim} has little bearing on the system response to the stimulus. Since the uncapped system response is stable at $k_{in} = -100$, increased modulation limits have no effect beyond a certain point. On the other hand, the responses for $k_{in} = -150$ are shown in Fig. 10b. This inertial gain was observed to be unstable for the stimulus and these results corroborate those findings. However, because the increased controller gain invites greater power modulation, ΔP_{lim} is effective here. Limits below approximately 10% mute the system response accordingly and the family of responses qualitatively resembles the one in Fig 10a, capping at 10% with a stable response, albeit with fairly significant oscillations. Beyond that, however, the system responses are indicative of loss of synchronism.

The same analysis was performed with the CE-SI control cases with and without communication latency in Fig. 11. In both cases, with the stable gain value $k_{in} = -100$, the effect of the ΔP_{lim} value is marginalized by the relatively small action



(a) $k_{in} = -100$.

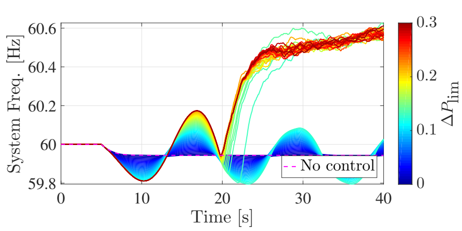


(b) $k_{in} = -150$.

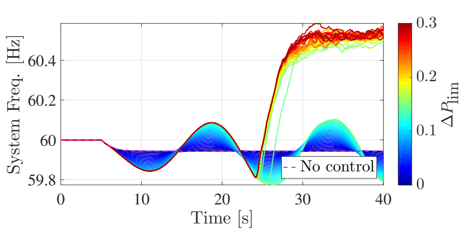
Fig. 10: System frequency response for the loss of generation event using synthetic inertia with limits on active power modulation.

demanded by the controller like in Fig. 10a. For the unstable gain of $k_{in} = -150$, the limit ΔP_{lim} can once again be seen to be more effective; capping the active power modulation at up to approximately 11% of its original setpoint prevents the system from going unstable. Additionally, the impact of the 500 ms of communication latency on the CE-SI control case can be seen even on the higher power modulation limit simulations; the delayed action of the controller reduces the frequency of the induced oscillations and increases the time to instability, allotting more time for remediation.

Limiting ΔP_{lim} is effective in mitigating the adverse effects of inverting control actions. Depending on the aggressiveness of the control tuning, the amplitude of the power modulation is often a small fraction of the setpoint under normal operation. Even when not considering the possibility of controller misconfigurations, limiting power modulation would be a safe practice while not significantly impacting frequency regulation capabilities. For photovoltaic power, for example, the plants would not need to significantly curtail their power output to provide those services effectively; e.g., they could operate at 90% of their maximum output, cap power modulation to 10% of that amount, and provide enough power modulation in both directions as demanded by the controller.



(a) With no latency.



(b) With 500 ms of latency.

Fig. 11: System frequency response for the loss of generation event using CE-SI with $k_{in} = -150$ and limits on active power modulation.

IV. Conclusions

This paper analyzes the impact on power system frequency response when its CIGs, composing a significant share of its generation, have their frequency response controls misconfigured. In the test system analyzed, CIGs provide frequency regulation support via different control schemes, specifically frequency droop, synthetic inertia, and feed-forward control. The results of the simulations performed for each of the control schemes show the feedback control schemes, frequency droop and synthetic inertia, are particularly sensitive to poorly tuned parameters, particularly if they create positive feedback. For these two control cases, the system may lose synchronism if the positive feedback is strong enough. The results for the feed-forward control case, CE-FAIR, show that this control scheme is more tolerant to parameter misconfiguration. This paper also shows that imposing limits on the amount of active power to be controlled is effective in mitigating the harmful effects in the scenarios considered.

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