

Analysis of Virtual Load Damping Provision from IBR-Dominated Distribution Networks

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Abstract—Virtual load damping is a valid alternative to virtual inertia to ensure frequency support in low-inertia power systems. We show that virtual load damping can be provided by multiple small power/capacity inverter-based resources. This can be obtained by exploiting inverter-based resources installed at domestic utilities in distribution feeders, which integrate renewable energy sources. Assessing the impact of these units on frequency requires changing the paradigm used to study power grid stability, since feeders need to be simulated in detail and cannot be represented with equivalent load models anymore, as was done in the past. Time-domain analyses of modified versions of the IEEE 14-BUS and MINIWEC power system benchmarks, obtained by the addition of several feeders in different virtual load damping scenarios, are included to support our claims.

I. INTRODUCTION

The ongoing worldwide deployment of inverter-based resources (IBRs) fuelled by renewable energy sources (RESs) is rapidly changing many facets of electric power systems, ranging from operation, to control and to simulation. Among others, this trend is causing the displacement of conventional (synchronous) generators, which constitute the main source of mechanical inertia. This parameter, together with the load damping given by frequency-dependent loads, is mainly responsible for limiting frequency variations due to power mismatches. The resulting decrease in inertia makes frequency control more challenging and ultimately threatens power system stability [1].

Virtual inertia is one of the most popular countermeasures proposed to address this issue [2]. It consists in modifying the control scheme of IBRs so that their power response is dependent on the derivative of the grid frequency and mimics the swing equation ruling the dynamics of synchronous generators [3]. Apart from inertia, frequency support can also be contributed by load damping [4]–[6], which can be provided by IBRs in the form of *virtual* load damping [7], [8]. In this context, the availability of a large share of IBRs fuelled by renewables and scattered in distribution feeders is a very precious resource. Indeed, through virtual load damping, each IBR unit can react to power mismatches and help limiting frequency deviations, even in low-inertia power systems.

However, despite its clear potential, this solution calls for new approaches to analyze power system stability. The

reason for this is that power mismatches that trigger frequency deviations are *local* events, which immediately cause a *local* electrical frequency variation due to a voltage/current phase shift. Based on the above, it is reasonable to assume that each IBR in distribution networks that provides virtual load damping may react differently to a *local* disturbance. This implies that validating the effectiveness of virtual load damping provision in these cases requires simulating IBR-dominated feeders in detail. This is in contrast with classic approaches for large-scale power system analysis, where distribution feeders are replaced with equivalent load models to reduce the computational burden and complexity of simulations. The reliance on this traditional approach would otherwise result in overlooking the possible interactions between distribution feeders and the transmission network during frequency dynamics.

In this paper, we investigate the above aspects and show that virtual load damping provided by small residential IBRs can offer a very effective support to fast frequency response, thus reducing the need for inertia (be it mechanical or virtual). To do so, we perform time-domain analysis of the IEEE 14-BUS and MINIWEC power system benchmarks, both modified by adding several feeders with a high penetration of IBRs, and consider the effects of different levels of virtual load damping provision from IBRs on frequency.

II. IBR CONTROL SCHEME

Figure 1 depicts the IBR control scheme model adopted in this work. It is a modified version of the one introduced in [9] and subsequently detailed in [10]. It implements a phase locked loop (PLL) to derive an internal frequency reference from the voltage v at the point of common coupling (PCC), and relies on active/reactive power, virtual impedance, and voltage/current controls to regulate the power exchange. We do not report the full set of equations of the model described in [10], but rather limit ourselves to mentioning only the modifications we introduced, that were needed for the implementation of virtual load damping.

Contrary to [10], which uses a three-phase average model of a voltage source converter (VSC), here we use a single-phase model, as our focus is on residential renewable-based IBRs in distribution feeders. As to the IBR control scheme shown in Fig. 1, it can be described as follows: first, we applied low-pass filters (LPFs) to the angular speed ω_{pll} detected by the

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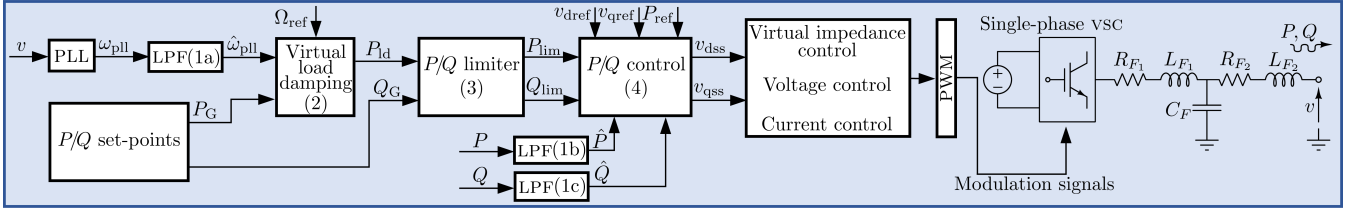


Fig. 1. IBR control scheme. Details on the implementation of the PLL, virtual impedance, voltage, and current controls can be found in [10].

PLL and the IBR active and reactive power exchange P and Q . The filtering is implemented as

$$\frac{d\hat{\omega}_{pll}}{dt} + \Omega_{ld}(\hat{\omega}_{pll} - \omega_{pll}) = 0 \quad (1a)$$

$$\frac{d\hat{P}}{dt} + \Omega_F(\hat{P} - P) = 0 \quad (1b)$$

$$\frac{d\hat{Q}}{dt} + \Omega_F(\hat{Q} - Q) = 0, \quad (1c)$$

where Ω_{ld} and Ω_F are the LPF cut-off frequencies, and the $\hat{\cdot}$ symbol denotes low-pass filtered variables.

The IBR active power set-point P_G (in per-unit, [pu]), together with $\hat{\omega}_{pll}$, are used by the virtual load damping control scheme to provide an updated active power reference value P_{ld} as

$$P_{ld} = P_G + \kappa_d(\Omega_{ref} - \hat{\omega}_{pll}), \quad (2)$$

with the $_{ld}$ label denoting (virtual) load damping. This control, regulated by the parameter κ_d , is such that P_{ld} deviates from P_G based on the difference between the nominal angular speed Ω_{ref} and $\hat{\omega}_{pll}$, as in a droop control. In (2), $\hat{\omega}_{pll}$ is used instead of its unfiltered counterpart ω_{pll} to reduce the sensitivity of the virtual load damping control block to abrupt changes in the estimated angular speed of the PLL, which may occur during power system operation (e.g. faults).

The new reference value P_{ld} and the reactive power set-point Q_G (in [pu]) are limited by the apparent power limiter

$$P_{lim} = \begin{cases} P_{ld} & \text{if } \sqrt{P_{ld}^2 + Q_G^2} \leq A_{max} \\ \frac{P_{ld}A_{max}}{\sqrt{P_{ld}^2 + Q_G^2}} & \text{if } \sqrt{P_{ld}^2 + Q_G^2} > A_{max} \end{cases} \quad (3)$$

$$Q_{lim} = \begin{cases} Q_G & \text{if } \sqrt{P_{ld}^2 + Q_G^2} \leq A_{max} \\ \frac{Q_G A_{max}}{\sqrt{P_{ld}^2 + Q_G^2}} & \text{if } \sqrt{P_{ld}^2 + Q_G^2} > A_{max}, \end{cases}$$

where A_{max} sets the maximum apparent power that the IBR can exchange. In our case $A_{max} = 1.2$ [pu]. The addition of the apparent power limiter is mandatory since virtual damping can push the IBR beyond its thermal limits.

In turn, P_{lim} and Q_{lim} are used as inputs in the P/Q control block, which computes through a proportional controller of the gains κ_p and κ_q the reference voltages v_{dss} and v_{qss} , given by

$$v_{dss} = v_{dref} + \kappa_p P_{ref} (P_{lim} - \hat{P}) \quad (4)$$

$$v_{qss} = v_{qref} + \kappa_q P_{ref} (Q_{lim} - \hat{Q}).$$

In (4), P_{ref} is the rated power of the IBR, while v_{dref} and v_{qref} are the reference voltage values. Lastly, v_{dss} and v_{qss} are exploited by a sequence of control blocks (i.e., virtual impedance, voltage, and current control – whose implementation is identical to that of [10]) to obtain the inputs of the PWM block, which derives the modulation signals to operate the IBR as required.

III. SIMULATION ENGINE & SYSTEM CONFIGURATIONS

To assess the effect that IBRs equipped with virtual load damping and scattered in distribution feeders may have on frequency control, we consider as benchmarks the IEEE 8500-BUS feeder, whose schematic is shown in Fig. 2: we refer the interested reader to [11] for a complete description and its parameters. In the following analyses, we considered two scenarios, where the number of single-phase IBRs connected amounts to either 235 (as in Fig. 2) or 392. In both scenarios, the rated power of each IBR is the same as that of the load with which it shares the point of connection, which is chosen randomly. The active/reactive power set-points of all IBRs are $P_G = 0.9$ [pu] and $Q_G = 0$ [pu], respectively. These set-points are such that the power produced by IBRs is self-consumed by the neighbouring loads, thus lowering the total power absorbed at the feeder sub-station.

The IEEE 8500-BUS network is adopted to represent distribution feeders in two generation/transmission systems: the IEEE14 and the MINIWECC benchmarks. Their schematics are not shown for space reasons. The parameters of the IEEE14

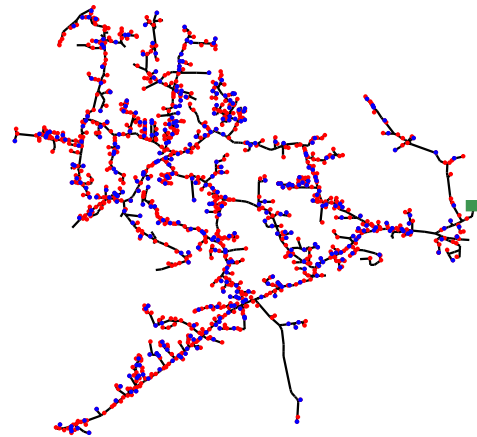


Fig. 2. The one-line diagram of the modified IEEE 8500-BUS feeder. The green marker denotes the sub-station, while the red and blue markers respectively indicate the loads and the randomly installed IBRs.

benchmark can be found in the distribution of PSAT [12], while the MINIWECC system was presented in [13] and its (reduced) model is available in MATLAB/SIMULINK.

In the case of the IEEE14 system, we replaced with the IEEE 8500-BUS feeder only the loads connected to 13.2 kV buses (the remaining ones operate at 69 kV and as such cannot be considered feeder sub-stations). We expanded the selected loads by entirely or partially substituting them with an IEEE 8500-BUS feeder¹.

IV. SIMULATION RESULTS

All the simulation results shown here were obtained with the PAN simulator [14] on a INTEL-I7@2.1 GHz computer running LINUX-MINT.

A. IEEE14 system

The parameter D (i.e., the damping [3]) of the swing equation of the synchronous generators G1 and G2 (i.e., the only ones of this kind in the IEEE14 system) was set to 0, so that only IBRs can contribute load damping to the network. G1 and G2 are equipped with turbine governors, which govern system frequency restoration after power mismatches. Their droop is 0.02, which corresponds to the $1/0.02$ steady-state gain.

To begin with, we performed eigenvalue analyses at the power flow solution (PFS). These analyses apply to the *linear* version of the power system model and show that, given a specific set of IBR parameters, the entire grid becomes unstable if more and more IBRs are put in service in the feeders. To be specific, when $\Omega_{ld} = 2.5$ Hz in equation (1a) and each feeder includes 235 IBRs, the entire grid is stable. On the contrary, the grid becomes *unstable* when the active IBRs rise to 392. To re-obtain stability, we must set $\Omega_{ld} = 2.0$ Hz.

The participation factors reveal that the unstable modes are due to the interactions among the PLLs of different IBRs in the same feeder. One could argue that this may be caused by our specific implementation: however, these behaviours were detected in several occasions (i.e., other IBR controls) and often PLLs were to blame [15]–[18]. Indeed, PLLs form a loop with the IBR controls involved with both active power regulation and virtual load damping. When these controls need to modulate the IBR power exchange, they do so by changing the instantaneous phase of the current i at the PCC, which causes a corresponding variation of the v voltage according to the connection strength. This stimulates the PLL (which relies, as shown in Fig. 1, on the voltage at the PCC to estimate ω_{pll}), which in turn drives the previous IBR controls. This loop, which may lead to instability, is known in the literature [16], [19]–[22], but a general tuning criterion of PLL parameters for preventing instability has not emerged yet². In any case, whatever the cause of instability might be,

¹The word “partially” means that we kept the original load and reduced its active/reactive power to balance the addition of the feeder, with the IBRs out of service.

²As stated in Section II, we mitigated this issue by using in the virtual load damping control block the low-pass filtered version of the angular speed ω_{pll} estimated by the PLL.

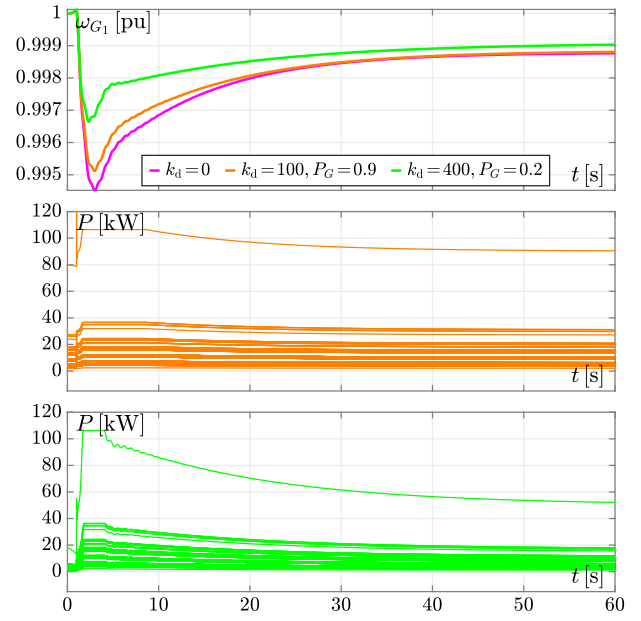


Fig. 3. Upper panel: the G1 rotor speed of the IEEE14 in different cases: $\kappa_d = 0$ - **magenta**, ($\kappa_d = 100$, $P_G = 0.9$) - **orange** and ($\kappa_d = 400$, $P_G = 0.2$) - **green**. Center panel: instantaneous active power of the 392 IBRs of the feeder connected at BUS6 in the “orange” case. Lower panel: same traces of the center panel but in the “green” case.

these results highlight that detailed analyses of IBR-dominated distribution feeders are necessary to assess the impact of virtual load damping on power system operation.

After performing eigenvalues analyses, we ran time-domain analyses for different scenarios by changing the value of κ_d governing virtual load damping (see (2)) and applied a large power imbalance by increasing by 50% both the active and reactive power of the L3 load at BUS3 of the IEEE14 system. The results of this simulation are shown in Fig. 3. In the upper panel of Fig. 3 we report the rotor speed of G1 (i.e., the generator with the largest capacity – 615 MVA) in different scenarios. The **magenta** trace refers to the scenario with $\kappa_d = 0$ (no virtual damping is provided). This scenario shows the conventional behaviour of the grid to the power imbalance and is used as “reference” to display improvements granted by virtual load damping. On the contrary, the **orange** and **green** traces refer respectively to the case when ($\kappa_d = 100$, $P_G = 0.9$) and ($\kappa_d = 400$, $P_G = 0.2$). It is worth noting that in these cases the value of κ_d is much higher than the droop of the turbine governors installed in G1 and G2. This implies that IBRs are expected to participate with significant active power variations to support frequency. The beneficial impact of virtual load damping provision through IBRs is clearly visible, as the **orange** and **green** traces are characterized by lower frequency deviations than the **magenta** one. In particular, the **green** trace has the slightest frequency deviations because, by lowering P_G from 0.9 to 0.2, the IBRs have a wider power margin for providing virtual load damping without risking output saturation due to the apparent power limiter in Fig. 1.

The traces in the upper panel have to be observed together with those in the center ($\kappa_d = 100$, $P_G = 0.9$) and lower

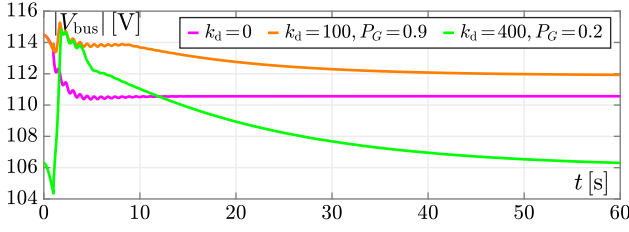


Fig. 4. Moduli of the voltages at a bus of the feeder connected at BUS6 if the IEEE14 system. Color code as in the upper panel of Fig. 3.

panels ($\kappa_d = 400$, $P_G = 0.2$). They show the instantaneous active power delivered by the 392 IBRs in the feeder connected to BUS6. Compared to the middle panel, the bottom one has less damped power oscillation. Both panels show that IBRs do not react in the same way to the power disturbance, as each of them varies their power exchange in a different way. Some IBRs are subject to power saturation due to the intervention of the apparent power limiter.

Lastly, Fig. 4 reports the magnitude of a bus voltage of a feeder in the same cases of Fig. 3. We see that in both cases ($\kappa_d = 100$, $P_G = 0.9$ and $\kappa_d = 400$, $P_G = 0.2$), the voltage peaks are equal due to power injection saturation. In all cases the voltages remain confined in the acceptance band. Checks on voltage limit violations are of interest in distribution feeders, mainly if RESS are present and there is a bidirectional energy flow at the sub-station.

B. MINIWECC

The IEEE14 system does not show any appreciable electrical distance: therefore, IBR behaviour in different feeders is almost identical due to a strong/stiff connection. On the contrary, the MINIWECC benchmark is much less “efficiently connected”. Thus, we do not expect IBRs of different feeders to behave in the same way. To verify this, we repeated transient stability analyses similar to those of the IEEE14 system by applying a power step increase (2 GW/0.856 GVAR) of the load at BUS34. Due to space limits, in Fig. 5 we only show the results obtained by letting $\kappa_d = 600$ and $P_G = 0.9$.

The upper panel depicts the rotor speeds of all the 16 synchronous generators. Right after the power imbalance, the speeds follow very different trends (i.e., they become *incoherent*). This affects the electrical frequency of feeders connected at different buses and the frequency support offered by their IBRs through virtual load damping. The middle panel shows the instantaneous active power of all the IBRs in the feeder at BUS34 (i.e., the same bus where the load step change occurs), while the bottom panel depicts the same traces but related to the feeder at BUS11, located far from the power imbalance. In the middle panel faster power variations and some saturations are evident, while in the bottom one the traces exhibit a slower variation in power exchange without any saturation. Once again, these results could not be captured by replacing distribution feeders with equivalent load models.

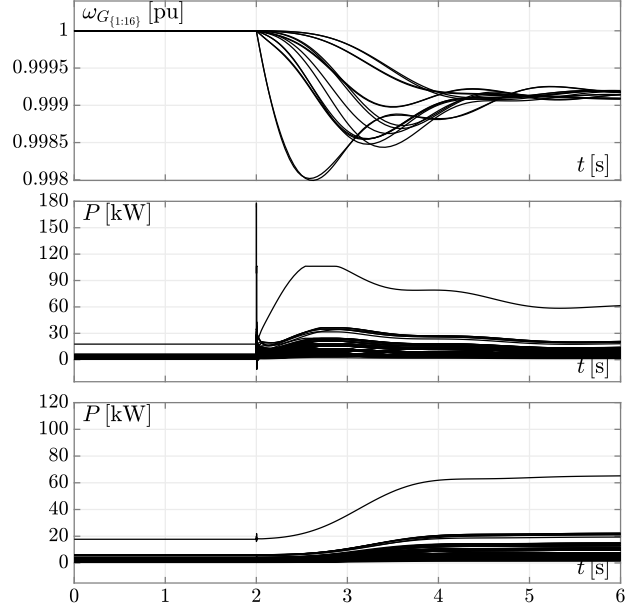


Fig. 5. Upper panel: rotor speeds of the 16 generator of the MINIWECC. Center panel: instantaneous active power of the 392 IBRs of the feeder connected at BUS34. Lower panel: instantaneous active power of the 392 IBRs of the feeder connected at BUS11.

V. CONCLUDING REMARKS

In this paper we have shown that IBR-dominated networks can provide satisfactory frequency support through virtual load damping, thus allowing to cope with the decreasing trend in inertia. Simulation results highlight that the response of IBRs to the same power disturbance may differ based on their location, even though their control parameters related to frequency support is the same. This suggests that damping (and we dare say also inertia) should be considered as a “local” quantity and not a “global” one referred to the entire grid. We believe that this aspect deserves further investigation [23].

Another aspect worth highlighting is that assessing the impact of IBRs and their controls on power system stability requires accurately simulating not only the transmission network, but also the distribution feeders. This, however, may lead to high computational costs. For example, the entire modified model of the IBR used in this work is implemented by a system of 64 differential algebraic equations. When 392 IBRs are in service in each IEEE 8500-BUS feeder, the IEEE14 system includes $7 \times 392 = 2744$ IBRs, which contribute $64 \times 2744 = 175616$ unknowns/equations (most of which are non-linear). Overall, the complete system comprises about 26000 lines, 8200 loads and 8200 transformers, which add up to a total of 419772 variables. In the case of the MINIWECC, this figure rises to 778944. This aspect calls for efficient approaches to the joint simulation of distribution and transmission networks, as well as distribution feeder reduction methods, which will be covered in future works.

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