Technical and Financial Assessment of Frequency Control for DERs Through Dynamic Simulations in OpenDSS

Vinicius C. Cunha*, Tiago R. Ricciardi*, Augusto Janssen, Fernanda C. L. Trindade**, Walmir Freitas**, Heliton O. Vilibor*** and Victor B. Riboldi*****

** ERA Energy Research and Analytics, Campinas, SP*
{vinicius.cunha, tiago.ricciardi}@eraenergy.com.br.
*** Universidade Estadual de Campinas, Campinas, SP*
a213358@dac.unicamp.br,{ferfeec, walmir}@unicamp.br
**** CPFL Energia, Campinas, SP*
{hdeoliveira, riboldi}@cpfl.com.br

Abstract: The Brazilian Independent System Operator oriented that frequency control will be soon requested from all distributed generators (DGs). In this context, this work proposes an approach to calculate the technical and financial impacts from the adoption of Watt-Hz curves in DGs for monthly simulations. This approach combines quasi-static time series (QSTS) simulations with dynamic simulations based on events that trigger the action of the frequency control. A real transmission and distribution (T&D) system comprising high voltage (HV) subtransmission lines, medium voltage (MV) distribution feeders, and low voltage (LV) circuits altogether (72,240 nodes), is used as a test system. The DGs considered in this work are synchronous generators. Three different models (2nd-, 4th-, and 6th-order machine models) are implemented as user-written models in AltDSS through Python (DSS Extensions project). Overall, the results show that the technical and financial impacts tend to be minimal for both perspectives: DG owners (energy curtailment) and utilities (steady-state voltage transgressions and technical losses).

Resumo: O Operador Nacional do Sistema (ONS) orientou que sistemas de controle de frequência serão requisitados a todos geradores distribuídos (GDs). Nesse contexto, esse trabalho propõe uma abordagem para calcular os impactos técnicos e financeiros da adoção de curvas Watt-Hz em GDs considerando simulações mensais. Esta abordagem combina simulações série-temporais quase-estáticas (QSTS) com simulações dinâmicas, baseando-se na atuação do controle de frequência. Um sistema real transmissão-distribuição (T&D) consistindo em subtransmissão de alta tensão (AT), alimentadores de média tensão (MT) e sistemas de baixa tensão (BT) combinados (72.240 nós), é utilizado como sistema teste. Os GDs considerados são geradores síncronos. Três ordens de modelos (2ª, 4ª e 6ª ordem) são implementados como 'modelos de usuário' no AltDSS utilizando Python (projeto DSS Extensions). Os resultados mostram que os impactos técnicos e financeiros tendem a ser pequenos para ambas as perspectivas: acessantes (corte de energia gerada) e distribuidoras (transgressão de tensão em regime permanente e perdas técnicas).

Keywords: Distributed Generation, Distribution Systems, Dynamic Simulation, Financial Assessment, Watt-Hz Curves.

Palavras-chaves: Análise Financeira, Curvas Watt-Hz, Geração Distribuída, Simulação Dinâmica, Sistemas de Distribuição.

1. INTRODUCTION

The Brazilian Independent System Operator (ISO, in Portuguese, ONS) notified that frequency control will be requested from distributed generators (DGs) in the near future (ONS, 2021). This control will be requested from all generators connected to the distribution systems, from rooftop photovoltaic (PV) generators connected into low voltage (LV) systems, to inverter-based, induction, and synchronous generators connected to medium voltage (MV) systems.

The frequency control (Watt-Hz curve) requested by the ISO basically limits the output power of a DG during transient conditions in which generation exceeds the power consumption, resulting in overfrequency. On the other hand, there is no requirement for DGs to contribute in underfrequency scenarios, therefore these generators typically operate at their maximum power capacity or do not have dispatchability (ONS, 2021). The challenge of this request is how to quantify, through simulations, the potential technical and financial impacts for utilities and DG owners. Utilities may be interested in how the Watt-Hz control on DGs affects the technical losses and steady-state voltages transgressions on customers, resulting in operational costs. On the other hand, DG owners may be interested in how the Watt-Hz control on DGs curtails their energy generation, resulting in revenue loss.

Therefore, tools that can handle dynamic simulations with detailed models of DGs and distribution systems (subtransmission, MV, and LV systems) are desired. For example, OpenDSS, which is a tool used typically for quasi-static time series (QSTS) simulations, can handle dynamic simulations with some built-in models (e.g., generator model) (EPRI, n.d.). There are some works in the literature that propose user-written models to add or improve existing dynamic models on OpenDSS (Argüello et al., 2018; Nagarajan and Ayyanar, 2014; Yu et al. 2019).

In this context, this work proposes an approach to calculate the technical and financial impacts for the adoption of Watt-Hz control in DGs for long-term simulations (e.g., daily-to-monthly basis). This approach combines QSTS simulations with dynamic simulations based on events that trigger the Watt-Hz control operation. A real transmission-distribution (T&D) system comprising high voltage (HV) subtransmission lines, MV distribution feeders, and LV systems altogether (72,240 nodes), is used as a test system. The DGs considered in this work are synchronous generators. Three different models (2nd-, 4th-, and 6th-order machine models) are implemented as user-written models through Python (AltDSS, DSS Extensions project (Meira, n.d.)). The OpenDSS used for the simulations runs on Windows through the DSS Python module (Meira, n.d.). To sum up, the contributions of this work are:

- A simplified approach to combine dynamic and QSTS simulations, calculating the monthly technical and financial impacts of the Watt-Hz control operation on DGs energy curtailment, steady-state voltage transgressions, and technical losses.
- The development of user-written models through DSS Extensions, allowing the *Initialization*, *Integration* and *Calculation* functions of the machine models be fully developed in Python (user-friendly).

This paper is organized as follows. Section 2 presents the Watt-Hz curve requested by the ISO and the costs formulation. Section 3 describes the dynamic models for synchronous generators implemented through the DSS Extensions. Section 4 presents the method to calculate the financial impacts that may occur due to the Watt-Hz control operation. Section 5 describes the test system used. Section 6 presents and discusses the findings of this work. Section 7 concludes this work.

2.FREQUENCY CONTROL AND COSTS OF TECHNICAL IMPACTS

The frequency control (Watt-Hz curve) requested by the ISO is shown in Fig. 1. If overfrequencies occur in the system, exceeding 60.2 Hz, the Watt-Hz control (Fig. 1) will act on the DGs, limiting their power output. Therefore, the customers that own a DG may be financially impacted. Note that most of the frequency fluctuations from load/generation imbalance will not trigger this control, as the frequency is expected to be within the adequate range of 59.9 Hz and 60.1 Hz (Brazilian regulation). The formulation of the costs considering energy curtailment is shown in Section 2.1. Additionally, utilities may want to validate that the Watt-Hz control operation on DGs does not cause additional costs, such as compensation costs with overvoltages transgressions and increase of technical losses costs. These costs are formulated in Sections 2.2 and 2.3, respectively.

2.1. Costs of Energy Curtailment

The Watt-Hz control acts when overfrequency occurs, i.e., the generation exceeds the power consumption in the system. Therefore, DG owners may be impacted by energy curtailment. The expression that transforms the curtailments into costs is shown below,

$$C_{cur} = (TUSD + TE)E_{cur}, \quad (1)$$

where C_{cur} is the cost of energy not generated by the DG owner, $TUSD$ (US$/MWh) is the tariff related to the utilization of the distribution system, TE (US$/MWh) is a tariff related to the energy consumption, and E_{cur} (MWh) is the energy curtailed by the Watt-Hz control action.

2.2.Voltage Transgression Compensation Costs

The voltage transgressions occurs when the measured voltages on a customer violate the adequate limits for a certain period, as defined in Table 1. The voltage measurements are classified as precarious (DRP) or critical (DRC), following the formulation below,

$$DRP = \frac{nlp}{NTL} \times 100\%, \quad (2)$$

$$DRC = \frac{nlc}{NTL} \times 100\%, \quad (3)$$

where nlp and nlc are the number of voltage measurements, averaged in 10-minute windows, that are classified in the precarious and critical range, respectively, and NTL is the total number of voltage samples.

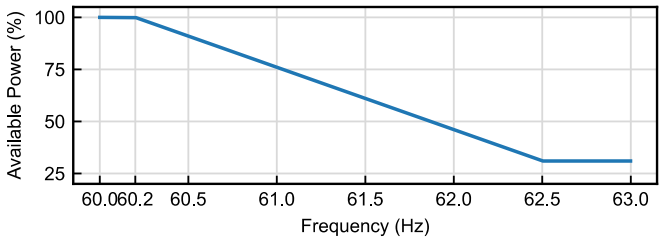

Fig. 1. Watt-Hz curve proposed by the ISO, limiting the injection of active power (3% gain per 0.1 Hz).

Table 1. Regulatory Voltage Limits for MV Customers (1kv ≤ V < 69 kv) and LV Customers (V < 1kv).

Operational Range	MV Customer		LV Customer	
	Voltage (pu)	Duration (%)	Voltage (pu)	Duration (%)
Critical Overvoltage	V>1.05	>0.5	V>1.06	>0.5
Precarious Overvoltage	-	-	1.05≤V<1.06	>3.0
Adequate Voltage	0.93≤V≤1.05	-	0.92≤V≤1.05	-
Precarious Undervoltage	0.90≤V<0.93	>3.0	0.87≤V<0.92	>3.0
Critical Undervoltage	0.90<V	>0.5	0.87<V	>0.5

The monthly voltage transgression compensation cost (C_{comp}^{mon}) for a customer is calculated as shown below,

$$C_{comp}^{mon} = \left[\left(\frac{DRP-DRP_{LIM}}{100}\right).k_1 + \left(\frac{DRC-DRC_{LIM}}{100}\right).k_2\right].EUSD, \quad (4)$$

$$EUSD = TUSD.E_{kWh}, \quad (5)$$

where DRP_{LIM} is 3% and DRC_{LIM} is 0.5% (Table 1); k_1 is 3 if DRP > DRP_{LIM}, otherwise is 0; k_2 is 5 for MV customers and 7 for LV customers if DRC > DRC_{LIM}, otherwise is 0; $EUSD$ (US$) is the cost related to the utilization of the distribution system; E_{kWh} (MWh) is the energy consumed by the customer in the month in which the measurements were performed.

2.3.Technical Losses Costs

The costs of the technical losses (C_{TL}) are defined by the multiplication of the technical energy losses (MWh) and the average cost of energy purchased ($T_{mix}^{average}$) by the utility in its last contracts. This expression is formulated as follows,

$$C_{TL} = E_{TL}.T_{mix}^{average}. \quad (6)$$

3.DYNAMIC MODELS OF SYNCHRONOUS GENERATORS USING DSS EXTENSIONS

The dynamic models of synchronous generators, based on (Milano, 2010), are fully implemented on Python. Second-, 4th-, and 6th-order machine models are developed, as shown on Sections 3.1, 3.2, and 3.3, respectively. Additionally, the turbine speed governor from (Milano, 2010) (type 2) is developed in Section 3.4, including the Watt-Hz control.

The main advantages of using OpenDSS (DSS Extensions) for these dynamic studies are: (i) easy to implement detailed models for distribution systems (HV, MV, and LV systems altogether); and (ii) the DSS Extensions allows the *Initialization*, *Integration* and *Calculation* functions of the machine models be fully developed in Python (user-friendly). If needed, the Python implementation can be replaced by a DLL (requires another programming language).

3.1.Second Order

The 2nd-order synchronous machine model (classical electromechanical model) neglects all electromagnetic dynamics, even in the machine rotor (Milano, 2010). Therefore, the dynamic equations are related to the inertia response (swing equations), as shown below,

$$\dot{\delta} = \omega_b(\omega - \omega_{ref}) \quad (7)$$

$$\dot{\omega} = \frac{1}{2H}\left(-T_{el} + T_m - D(\omega - \omega_{ref})\right) \quad (8)$$

where δ is the rotor angle, ω_b is the base of synchronous frequency, ω is the machine angular speed, ω_{ref} is the reference frequency, H is the inertia constant, T_{el} is the electromagnetic torque, T_m is the mechanical torque, and D is the damping coefficient.

In addition, the algebraic equations of the electromagnetic torque and the currents on the *dq0* reference frame (i_{dq}) are shown as follows,

$$T_{el} = (v_q + R_s i_q)i_q + (v_d + R_s i_d)i_d, \quad (9)$$

$$\begin{pmatrix} i_d \\ i_q \end{pmatrix} = \frac{1}{R_s^2 + x_d'^2}\begin{pmatrix} R_s & x_d' \\ -x_d' & -R_s \end{pmatrix}\begin{pmatrix} -v_d \\ e_q' - v_q \end{pmatrix}, \quad (10)$$

where v_{dq} are voltages on the *dq0* reference frame, R_s is the armature (stator) resistance, x_d' is the d-axis transient reactance, and e_q' is a constant emf behind the transient reactance (internal voltage).

3.2.Fourth Order

The 4th-order machine model shown in this section has a substantial agreement in the literature (Milano, 2010). In addition to the inertia response (7) and (8), there are two dynamic equations related to the dynamics of magnetic flux linkage in the rotor, represented by one circuit in the d- and another in the q-axis included in this model, as shown below,

$$\dot{e}_q' = \left(-e_q' - (x_d - x_d')i_d + v_f\right)/T_{d0}', \quad (11)$$

$$\dot{e}_d' = \left(-e_d' - (x_q - x_q')i_q\right)/T_{q0}', \quad (12)$$

where e_{dq}' are constants emf behind the transient reactances, x_q' is the q-axis transient reactance, x_{dq} are the dq-axes synchronous reactance, v_f is the field voltage, and T_{dq0}' are d-axes open circuit transient time constants.

The algebraic equations of the electromagnetic torque and the currents on the *dq0* reference frame (i_{dq}) for the presented 4th-order machine model are shown as follows,

$$T_{el} = e_d' i_d + e_q' i_q + (x_q' - x_d')i_d i_q, \quad (13)$$

$$\begin{pmatrix} i_d \\ i_q \end{pmatrix} = \frac{1}{R_s^2 + x_q' x_d'}\begin{pmatrix} R_s & x_q' \\ x_d' & R_s \end{pmatrix}\begin{pmatrix} e_d' - v_d \\ e_q' - v_q \end{pmatrix}, \quad (14)$$

3.3.Sixth Order

The 6th-order machine model is based on the Anderson-Fouad's model (Anderson and Fouad, 2002). In addition to the equations considered for the 4th-order model ((7), (8), (11), and (12)), there are two extra dynamic equations related to one additional circuit in each axis, to model not only the transient but also the subtransient dynamics of magnetic flux linkage in the machine rotor, as shown below,

$$\dot{e}_q'' = \left(-e_q'' + e_q' - (x_d' - x_d'')i_d\right)/T_{d0}'', \quad (15)$$

$$\dot{e}_d'' = \left(-e_d'' + e_d' + (x_q' - x_q'')i_q\right)/T_{q0}'', \quad (16)$$

where e''_{dq} are constants emf behind the subtransient reactances, x''_{dq} are the dq-axes transient reactances, and T''_{dq0} are d-axes open circuit subtransient time constants.

The algebraic equations of the electromagnetic torque and the currents on the *dq0* reference frame (i_{dq}) for the presented 6th-order machine model are shown as follows,

$$T_{el} = e''_d i_d + e''_q i_q + (x''_q - x''_d) i_d i_q, \quad (17)$$

$$\begin{pmatrix} i_d \\ i_q \end{pmatrix} = \frac{1}{R_s^2 + x''_q x''_d} \begin{pmatrix} R_s & x''_q \\ x''_d & R_s \end{pmatrix} \begin{pmatrix} e''_d - v_d \\ e''_q - v_q \end{pmatrix}, \quad (18)$$

3.4.Turbine Governor

Turbine Governors are responsible for the frequency control of synchronous machines. The static droop (R) is defined to set the Watt-Hertz curve. It determines the participation of each machine to system losses and load power variations (Milano, 2010). The Type II model (Milano, 2010) is implemented, where the following equations are included,

$$\dot{x}_g = \left(\frac{1}{R}\left(1 - \frac{T_1}{T_2}\right)(\omega_{ref} - \omega) - x_g\right)/T_2, \quad (19)$$

$$\hat{T}_m = x_g + \frac{1}{R}\frac{T_1}{T_2}(\omega_{ref} - \omega) + T_{m0}, \quad (20)$$

where T_1 is the transient gain time constant, T_2 is the governor time constant, T_{m0} is the initial mechanical torque determined when initializing synchronous machines. The mechanical torque $\hat{T}_m$ is limited within a minimum (T^{min}) and a maximum (T^{max}) values, respecting the operational limits.

4.METHOD FOR CALCULATING THE FINANCIAL IMPACTS ON CUSTOMERS AND DISTRIBUTION UTILITIES

The main challenge of calculating the financial impacts of applying a Watt-Hz control on DGs is to consider an adequate simulation horizon. The costs of voltage transgressions, technical losses, and energy curtailment are better represented on, at least, a monthly basis. On the other hand, dynamic simulations with high resolution (e.g., few ms) are impractical to be run for an entire month.

To deal with this issue, a hybrid simulation approach, that is, dynamic and QSTS simulations combined, is proposed. First, a monthly QSTS simulation is executed, storing the technical parameters, such as voltages on customers and technical losses on the system. In the QSTS simulation, typical loadshapes are used for customers based on their groups (residential, commercial, industrial) and a typical biomass generation loadshape for the DGs, both with 10-min resolution. In this case, there is no energy curtailed on the DGs, as the system is operated within the adequate frequency range (i.e., between 59.9 Hz and 60.1 Hz, according to Brazilian regulation). The time step for the QSTS simulations is defined as t_{QSTS}, corresponding to the integration time used to evaluate steady-state voltages (10 min in the Brazilian regulation).

In the sequence, dynamic simulations are executed. As the Watt-Hz control is not expected to act during the normal operation of the system, events that cause frequency swings (such as faults) are considered. Therefore, for each event, a dynamic simulation window with total period of t_{dyn} is created, storing the technical parameters, such as voltages on customers, technical losses on the system, and energy curtailed on DGs. To facilitate the integration of the QSTS and dynamic simulations, t_{dyn} is defined equal to t_{QSTS}.

Fig. 2 illustrates the process of combining the QSTS and dynamic simulations. The dynamic simulations windows, created based on events, replace a time step of the QSTS simulation. Therefore, for these time steps, the technical parameters obtained in the dynamic simulation replace the ones obtained in the QSTS simulation. Finally, the financial impacts in a month horizon, as formulated in Section 2, are calculated.

This hybrid approach represents a compromise solution between detailed modeling (DGs, shown in Section 3, and distribution systems, shown in Section 5) and the computational processing time. Another advantage of this approach is the straightforward implementation of stochastic evaluations, such as Monte Carlo methods. For example, the number of events (dynamic simulations) and the type of events can be considered as random variables, resulting in statistical results for the monthly calculated costs.

5.T&D TEST SYSTEM

The test system is a real Brazilian subtransmission and distribution systems modeled altogether (combined T&D system). The topology of the subtransmission is shown in Fig. 3. This 138 kV system is operated radially. There are six distribution substations in this subtransmission system, which five of them are represented by equivalent models (aggregated loads and aggregated 5MW-DGs) and one substation is modeled in detail (detailed MV and LV system models).

Substation 1 is chosen to be represented in detail. Its MV topology is shown in Fig. 4. This substation has a 25-MVA power transformer (138 kV/11.9kV) supplying five MV feeders (72,240 nodes). There are 12,671 customers (MV and LV customers) and the total length of the primary system is 235 km. In the MV distribution system, seven 2-MW DGs are included, considering or not the Watt-Hz control in all DGs, depending on the evaluated case.

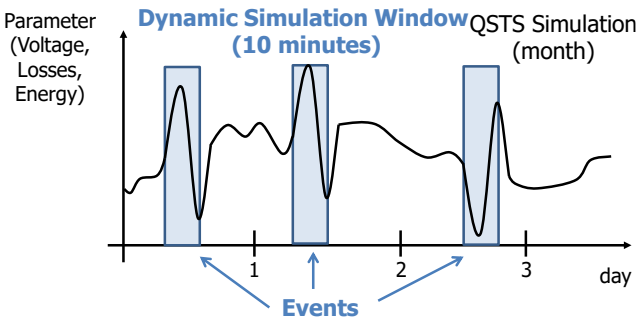

Fig. 2. Illustration combining the dynamic and QSTS simulations, that is, replacing the QSTS parameters for the ones obtained in the dynamic simulations.

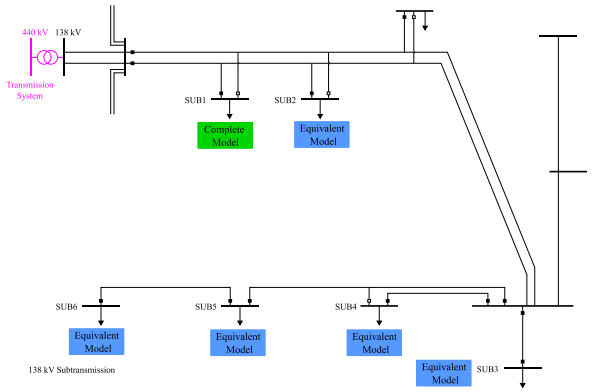

Fig. 3. Subtransmission topology (radially operated).

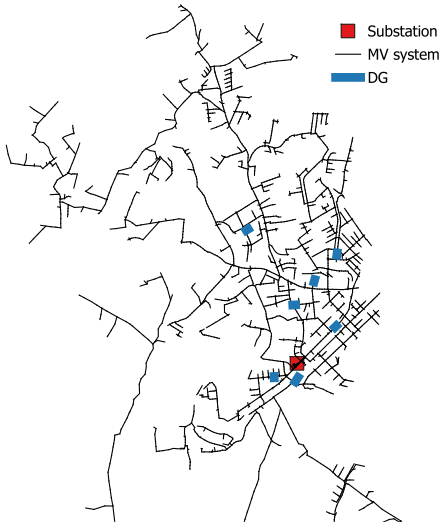

Fig. 4. MV system topology for the substation 1, shown in the substransmission system.

Although the DGs are considered only in the MV systems, the LV systems are modeled in detail as well because the utility may want to quantify the voltages transgressions on LV customers caused by these DGs. With this modeling approach, LV generation such as rooftop PV systems could be easily integrated into the simulated system.

6.RESULTS AND DISCUSSIONS

Many sensitivity studies have been conducted to quantify the technical and financial impacts of the Watt-Hz curve operation. For example, an extensive evaluation considering different parameters for the synchronous machines; different feeders assessed; different number of DGs per feeder and their capacity; different system conditions (e.g., stronger and weaker equivalent) were conducted. Due to limited space, an example of a disturbance caused by a fault in the subtransmission level is shown. The findings shown in this case are an adequate representation of all cases assessed.

6.1.Illustration of the Synchronous Machine Models

Table 2 shows the parameters used to model the 2nd-, 4th-, and 6th-order synchronous machines. The assumed values are standard ones found in (Milano, 2010) and (Kundur, 1994). To illustrate the dynamic response of the three machine models,

Table 2. Synchronous Machine Parameters.

Parameter	Value	Parameter	Value	Parameter	Value
x_d	0.9106 pu	T'_{d0}	2 s	$\boldsymbol{R_s}$	0 pu
x_q	0.4659 pu	T'_{q0}	1 s	$\boldsymbol{T_1}$	0.01 s
x'_d	0.5 pu	T''_{d0}	0.05 s	$\boldsymbol{T_2}$	0.001 s
x'_q	0.5 pu	T''_{q0}	0.05 s	$\boldsymbol{V_{nom}}$	12 kV
x''_d	0.1295 pu	$\boldsymbol{H}$	3 s	$\boldsymbol{S_{nom}}$	2 MVA
x''_q	0.1378 pu	$\boldsymbol{D}$	0	R	0.0556 pu

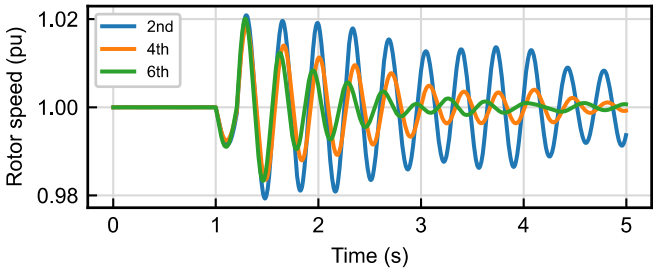

Fig. 5. Comparison of the dynamic responses for the 2nd-, 4th-, and 6th- order synchronous machines.

Fig. 5 shows the rotor speed for each one. In these simulations, a disturbance (i.e., fault) is considered at 1s, resulting in rotor speed oscillations. As expected, high order machine models damp more efficiently the oscillations, because with more rotor circuits being modeled, the higher is the damping effect.

6.2.Technical and Financial Evaluation for the Machines Modeled

The simulations from Fig. 5 are extended to a period of 10 min (i.e., t_{QSTS}) to evaluate the steady-state impacts on energy curtailment, voltage transgressions, and technical losses. These results are shown in Table 3. The deployment of the seven 2 MW DGs are shown in Fig. 4. The cases to assess the impacts due to the frequency response are: one case neglecting (NC) and one case considering (WC) the Watt-Hz control.

For the DG owner side, the energy curtailed due to the Watt-Hz control is negligible regardless of the machine model selected. For example, the maximum energy curtailed is 0.8% for the 6th-order machine, not having a significant impact for the DG owner. For the utility side, the impacts on voltage transgressions and technical losses are also minimal regardless of the machine model selected. The voltage transgressions are slightly higher for the WC case because the event considered is a fault, which causes voltage sag on customers. Therefore, for some customers, the steady-state effect caused by the fault is the bare elimination of the voltage transgression, i.e., the steady-state voltage of some customers is close to the upper voltage limit. When the Watt-Hz control is considered, the voltage restoration for these customers is faster, resulting in the initial condition without the fault (i.e., upper voltage transgression).

As described in Section 4, the technical impacts are transformed into costs considering the number of events the Watt-Hz control acts in a month. Three cases are evaluated, that is, a single event (1 event), one event every two days (15 events), and one event per day (30 events). The results for the 2nd-order machine are shown in Table 4. Overall, the differences in the costs are minimal. For example, the highest

Table 3. Technical Evaluation of Parameters Considering the Cases (1) No Watt-Hz Control (NC) and With Watt-Hz Control (WC).

Machine Model	DG Case (MW)	DG Owner Side	Utility Side	
		Energy Generated (MWh)	Voltage Transgression (%cust.)	Technical Losses (MWh)
2nd order	14 (NC)	2.342	30.65	0.121
	14 (WC)	2.338	30.83	0.121
4th order	14 (NC)	2.342	30.82	0.121
	14 (WC)	2.338	31.13	0.121
6th order	14 (NC)	2.342	30.87	0.121
	14 (WC)	2.324	32.28	0.120

Table 4. Financial Evaluation Considering the Difference Between the Cases NC and WC for the 2nd-Order Machine.

Number of Events	DG Case (MW)	DG Owner Side	Utility Side	
		Energy Generated (USD)	Voltage Transgression (USD)	Technical Losses (USD)
1	14	0.30	3.85	0.00
15	14	4.42	57.74	0.03
30	14	8.84	115.47	0.06

difference occurs for the voltage transgression considering 30 events, which only represents 0.008% of the total costs of voltages transgressions. As expected, the Watt-Hz control marginally impacts DG owners and utilities.

7.CONCLUSIONS AND FUTURE WORKS

The proposed method, which combines QSTS and dynamic simulations, was efficient in calculating the technical and financial impacts of the Watt-Hz control operation on DGs. The DGs owners' perspective, i.e., DG energy curtailment, and the utility perspective, i.e., voltage transgressions and technical losses, were addressed. As expected, not only the technical, but also financial impacts for both perspectives tended to be minimal. Thus, under the evaluated conditions, the ISO request, i.e., the consideration of frequency control on DGs, does not tend to be a concern.

For future works, new dynamic models are planned to be included, such as inverted-based elements (energy storage systems, photovoltaic generators etc.), for dynamic simulations through the DSS Extensions project.

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