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Advanced dynamic stability system developed for nonlinear load

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ABSTRACT

The conventional production of electrical energy gives rise to environmental problems and involves high production costs. To cope with the increasing demand for electrical loads and to optimize power transmission on the grid, it is imperative to shift towards renewable energies and their hybrid utilization. This planning study assesses the impact of fluctuating electric loads on bus voltages and frequency, with the objective of distributing energy in a more efficient and dynamic manner. Moreover, we delve into the implementation of artificial intelligence (IAPS) to curtail operations, minimize losses (GED), optimize production plans (EMSO), and synchronize decentralized multi-machine power systems (MMSA). Our study scrutinizes power dispatching on dynamic models of purely consuming loads, which are subject to dynamic constraints, by utilizing educational software that encompasses 13 cycles for 24 hours of frequency studies for multisource production in a standardized electrical system (EPSS). The control outcomes obtained through validation on an IEEE30 bus network display a resilient model for planned productions.

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1. INTRODUCTION

Dispatchers face a problem of voltage stability and frequency fluctuations, especially during high load periods. Models of nonlinear electrical loads under critical transient conditions play a large role in the modeling and operating control equations of an electrical system [1]–[3]. Smart grid management or machine learning inelegance all depend on the consumption load pattern [2], [4], [5], which in turn directly affects the quality of use of the power system. On the latter, we can clearly model that the overall energy produced in normal cases is the sum of all consumption with transit losses [6].

In practice, there are two ways to optimize the control of electrical energy, either by controlling the consuming loads, which can therefore be difficult to envisage, or by optimally managing electricity production on the electrical networks [6], [7]. By modeling the evolution of electrical loads with respect to time, we can study the distribution and distribution of energy in a more efficient way, we can also exploit artificial intelligence to reduce operations, reduce losses, optimize production plans and synchronize decentralized multi-machine feed systems [7]. The characteristics of modern loads change over the course of a day, weeks and seasons, which makes estimating a suitable load model a very complicated operation [8], [9], especially with emerging smart grid technologies such as generators (DG), electric vehicles (EV) and demand side management (DSM) [10]. However, the variation and increase of the electrical loads demanded requires system operators and academic researchers to develop reliable optimal solutions to the problems related to nonlinear models through the management on the autotransformers (LTC) [11], the adaptation and the decentralize generation planning, reactive compensation devices FACTS [12], [13], transmission with HVDC, to ensure power distribution (OPF) on critically loaded distribution networks [14].

Then, the uncertainty in load modeling stems from the large number of diverse load components, time-varying and weather-dependent compositions [14], and the lack of detailed measurements and information on the load. load [15], [16]. Otherwise, the electric load pattern is classified into two main categories which are static or dynamic. The main types of load models are [5], [15]: i) static load models, ii) dynamic load models, iii) composite load models (CLM), iv) artificial neural network-based modeling, v) low-voltage (lv) load models, and vi) active distribution networks (ADNs) and MGs.

The static load model does not accurately reflect the shape of the load, as it only covers the static time behavior of the system; constant voltages, constant powers, and constant impedances. [17], [18]. When the traditional static load models are not sufficient to represent the load behavior, the alternative dynamic load models are needed [19], [20]. The study of this model allows to have a very detailed idea on the network in real time [21]. In this axis, we aim at the load model depending on the variation of the frequency [5], [20].

ZIP model is commonly used in both steady state and dynamic studies [21]. This model represents the relationship between the voltage magnitudes and power in a polynomial equation that combines constant impedance (Z), current (I), and power (P) components [22]–[24].

$$\begin{cases} P = P_0\left[a_p\left(\frac{V}{V_0}\right)^2 + b_p\left(\frac{V}{V_0}\right) + c_p\right]\left[1 - k_{pf}\Delta f\right] \\ Q = Q_0\left[a_q\left(\frac{V}{V_0}\right)^2 + b_q\left(\frac{V}{V_0}\right) + c_q\right]\left[1 - k_{qf}\Delta f\right] \end{cases} \quad (1)$$

Where $P\ et\ Q$ are the active and reactive powers of the load for the operating voltage V; $P_0\ et\ Q_0$ are the active and reactive powers of the load for the nominal voltage V_0; a_p, b_p, c_p, a_q, b_q, c_q are the coefficients of the model; k_{pf} is the active power sensitivity parameter, this constant typically $k_{pf} \in [0,3]$; k_{qf} is the reactive power sensitivity parameter, this constant typically $k_{pf} \in [-2,0]$; Δf The frequency deviation.

The static model of electrical charges is very limited [23]–[28], hence the need to present the charges in the form of other dynamic models for the analysis of electrical networks. In this context, several research studies have been carried out based on the consumer load model for grid control, cited [29]–[39]. In Table 1 we present the main load models with the parameters, advantages and disadvantages of each model [27], [28].

Table 1. Loads types models with advantages and disadvantages

Type	Model	Parameters	Advantages (+), disadvantages (-)
Static Load Models	Impedance (Z), current (I), power (P), ZIP	6	+ Clear physical meaning + Simple
	Exponential	2	+ Easy to apply
	ZIP w/frequency	8	+ Can be combined with dynamic models easily to from composite models
	Exponential w/frequency	4	- Fails to represent dynamic loads accurately
	EPRI LOADSYN model	9	
Dynamic Load Models	Induction motor (IM)	8	+ Represent multiple dynamic loads with the same model
	Exponential recovery	6	- The models are based on response to the voltage disturbance which changes under different conditions

The dynamic load model is based on the variation of voltage and frequency [21], [40]. We need the instantaneous values of the voltages and the frequencies so that we can have the new values of the active and reactive powers of demand [29]–[31]. The new voltage and frequency values are obtained through power flow calculations [28]–[35]. The proposed model is characterized by the coefficients, which play a very important role in the controllability of electrical networks. The production generators provide the necessary active and reactive powers according to demand while respecting the limitations of the reactive power generated [36]–[40].

Figure 1 presents the evolution of the global loads in all the PQ buses during 13 cycles with the initial case. Figure 2 presents the evolutions of the partial loads in certain buses during 13 cycles. Figure 3 shows the overall cycle power factors for all loads.

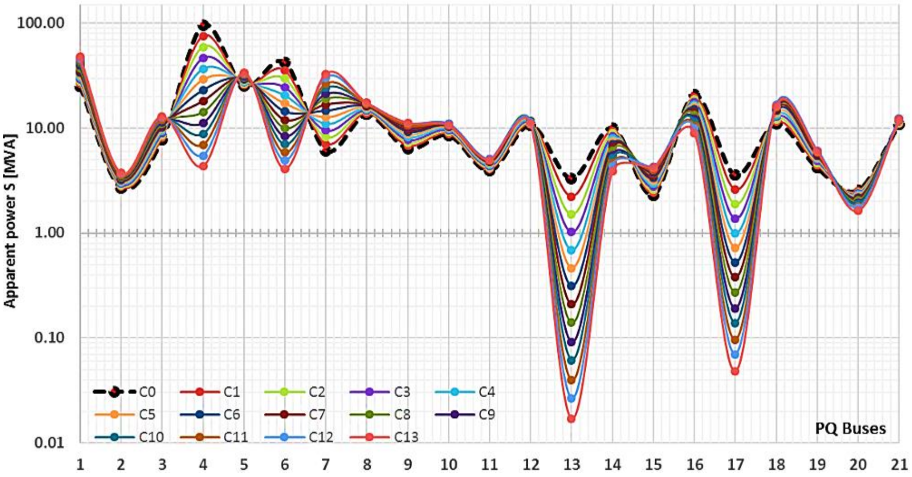

Figure 1. Global evolution of loads in all PQ buses for 220 minutes

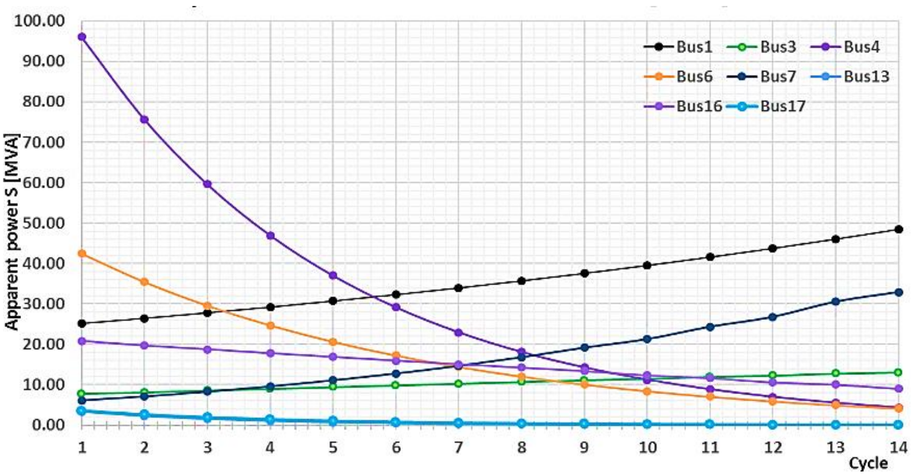

Figure 2. Loads evolutions in some buses for 13 cycles

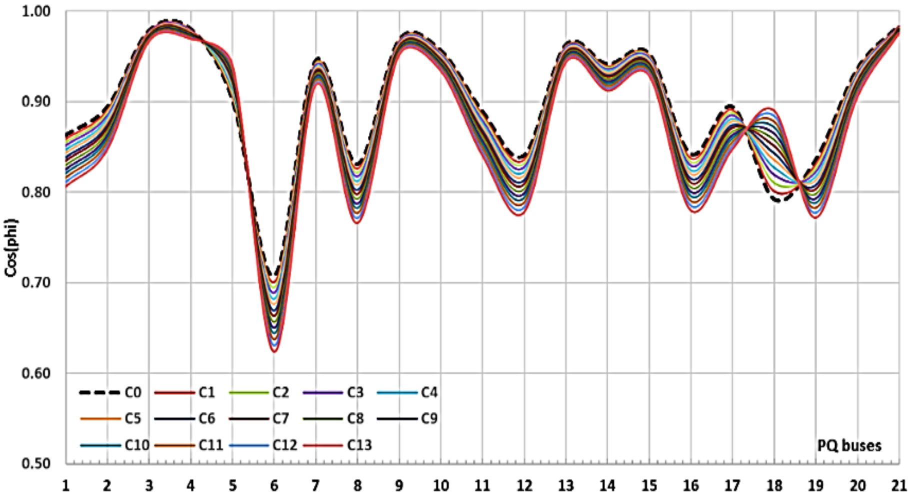

Figure 3. Global power factors per cycles for all loads

2. MATERIALS AND MATHEMATICAL FORMULATION

The production generators provide the necessary active and reactive powers according to demand while respecting the limitations of the reactive power generated.

$$\bar{S}_i = P_i + jQ_i = \left(P_{G_i} - P_{L_i} - P_{T_i}\right) + j\left(Q_{G_i} - Q_{L_i} - Q_{T_i}\right) \tag{2}$$

Where P_i, Q_i: active and reactive power at node I; P_{G_i}, Q_{G_i}: generation active and reactive power at node I; P_{L_i}, Q_{L_i}: active and reactive load power at node I; P_{T_i}, Q_{T_i}: active and reactive power transmitted; These powers are transmitted via the transport network.

$$\bar{S}_{ij} = |\bar{V}_i|^2 . \bar{Y}_{ij}^* - \bar{V}_i . \bar{V}_j^* . \bar{Y}_{ij}^* + |\bar{V}_i|^2 . \bar{Y}_{i0}^* \tag{3}$$

$$\bar{S}_{ji} = |\bar{V}_j|^2 . \bar{Y}_{ij}^* - \bar{V}_j . \bar{V}_i^* . \bar{Y}_{ij}^* + \left|\bar{V}_j\right|^2 . \bar{Y}_{j0}^* \tag{4}$$

Where $\bar{S}_{ij}$: apparent power transited from node i to node j; $\bar{S}_{ji}$: apparent power transited from node j to node i. Active and reactive losses are involved during power transmission.

$$\bar{S}_{Lossij} = \bar{S}_{ij} + \bar{S}_{ji}$$
$$\bar{P}_{Lossij} = R\left\{\bar{S}_{Lossij}\right\}$$
$$\bar{Q}_{Lossij} = Imag\left\{\bar{S}_{Lossij}\right\}$$

Where $\bar{S}_{Lossij}$ is apparent power lost in the branch (i-j), $\bar{P}_{Lossij}$ is active power lost in the branch (i-j), and $\bar{Q}_{Lossij}$ is reactive power lost in the branch (i-j).

$$\bar{S}_{Loss} = \sum \bar{S}_{Lossij}$$
$$\bar{P}_{Loss} = R\left\{\sum \bar{S}_{Lossij}\right\}$$
$$\bar{Q}_{Loss} = Imag\left\{\sum \bar{S}_{Lossij}\right\}$$

Where, $\bar{S}_{Loss}$ is total apparent power lost in the network, $\bar{P}_{Loss}$ is total active power lost in the network and $\bar{Q}_{Loss}$ is total reactive power lost in the network.

The controllers of the production generators adapt to the variations of the loads at every moment in order to ensure the continuity of service in the best conditions while maintaining the stability of the electrical grid, they follow a model of nature identical to that of the model of global load [29], [30]. This work reveals a dynamic study covering 13 cycles on the control of the models of the generators basing on the influence of the variations of the electric charges, the fluctuations of the tensions on the behavior of the distribution of the powers while controlling the parameters of the stability brought into play in the standard electrical system. The power flow calculations are used as basic data to carry out this study with two iterative calculation methods Fast Decoupled and Gauss Seidel.

The voltage equation in the buses expressed using the polar coordinate system, the complex voltage and the active and reactive powers can be written as follows:

$$\bar{V}_i = V_i\,(\cos\theta_i + \mathrm{j}\sin\theta_i)$$
$$\begin{cases} P_i = V_i \sum_{\mathrm{j}=1}^{\mathrm{n}} V_j\,(\mathrm{G}_{ij}\cos\theta_{ij} + \mathrm{jB}_{ij}\sin\theta_{ij}) \\ Q_i = V_i \sum_{\mathrm{j}=1}^{\mathrm{n}} V_j\,(\mathrm{G}_{ij}\sin\theta_{ij} - \mathrm{jB}_{ij}\cos\theta_{ij}) \end{cases} \tag{5}$$

where $\theta_{ij} = \theta_i - \theta_j$, the angle difference between buses i and j.

Assuming that the buses [1, 2, … m] are PQ buses, the buses [(m + 1), (m + 1), … (n-1)] are PV buses, and the nth bus is the balance bus. $V_n\ et\ \ \theta_n$ are given, and the amplitudes of the PV buses [V_{m+1}, V_{m+2}, … V_{n-1}] are also given. Then the bus voltage angles (n-1) are unknown and the voltage magnitudes are unknown. For each PV bus and PQ bus, we have in (6):

$$\begin{cases} \Delta P_i = P_{is} - P_i = P_{is} - V_i \sum_{\mathrm{j}=1}^{\mathrm{n}} V_j\,(\mathrm{G}_{ij}\cos\theta_{ij} + \mathrm{jB}_{ij}\sin\theta_{ij}) = 0 \\ \Delta Q_i = Q_{is} - Q_i = Q_{is} - V_i \sum_{\mathrm{j}=1}^{\mathrm{n}} V_j\,(\mathrm{G}_{ij}\sin\theta_{ij} - \mathrm{jB}_{ij}\cos\theta_{ij}) = 0 \end{cases} \tag{6}$$

Figure 4 presents the flowchart of the dynamic loads with the evaluation methods.

The production generators are controlled synchronously with load variations, taking into account all the constraints and limits of the subsystems. The main control lines per cycle are summarized in the Figure 4. Traditional and effective ways to reduce these problems are to derive additional signals for generator excitation systems and to compensate for fluctuations in power flow through transmission grids.

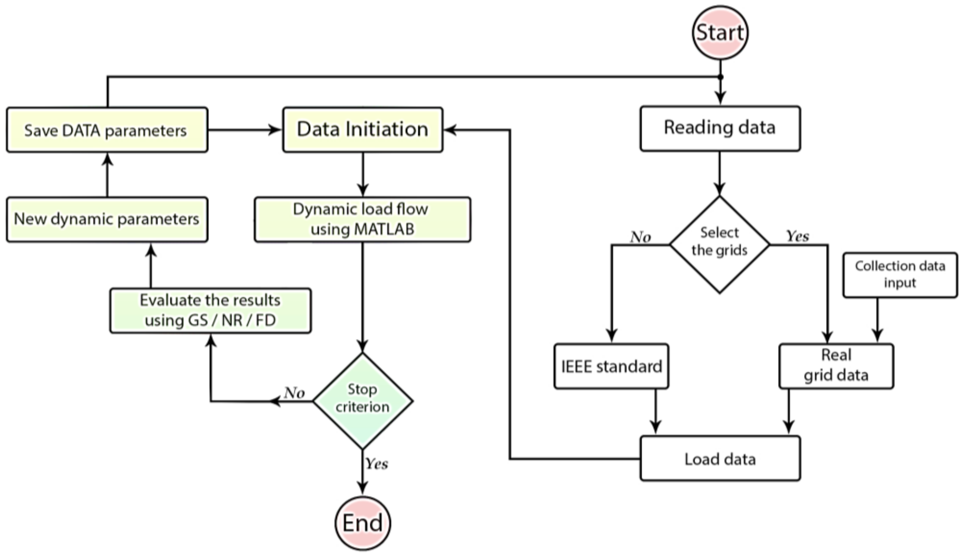

Figure 4. Flowchart of dynamic loads with evaluation methods

2.1. System description

The Figure 5 present the standardized IEEE 30 bus system is a well-known benchmark for power system analysis and research. This system grid is consisting of 30 buses, including generators, transmission lines, transformers, and loads. It provides a simplified representation of the system's electrical connectivity and helps in analyzing power flow, fault analysis, and other system studies. The standardized system (IEEE 30 bus) studied is composed as indicated in Table 2.

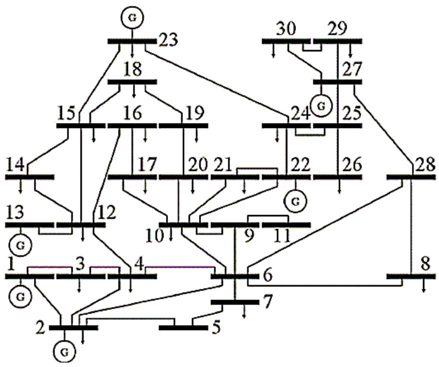

Figure 5. IEEE 30 bus standardized grid [27]

Table 2. Description of the study system

System characteristics		Number	Buses
Control Buses	SLACK BUS	01	1
	PV BUS	05	2, 5, 8, 11 and 13
	PQ BUS	24	-
branches		41	-
Generators	Thermal Generators	06	1, 2, 5, 8, 11 and 13
	Wind generators	0	0
	Solar PV system	0	0
Autotransformers		04	6-9, 6-10, 4-12 ,28-27
Shunts		02	10 and 24

2.2. Voltage control and transit limits

In Table 3, the lower and upper limits for voltage levels in a power system are typically defined to ensure the proper operation and stability of the system. These limits are specified to maintain voltage within a safe and acceptable range. Power transit limits for lines and autotransformers in a normal situation are 80% of the maximum.

Table 3. Marginal and critical voltage limits for voltage levels

Nominal voltage [kV]	Critical voltages situation	
	Lower [p.u.]	Upper [p.u.]
132, 33, and 11	0.9	1.1

3. RESULTS

The simulation results were studied and represented using the analysis of the values of the stability of small signals, dynamic voltages in the time domain and the methods of resolution (GS and FD load flow recursive) of the electrical system IEEE 30 bus on the MATLAB environment. The basic models of the loads as well as the production machines and the synchronism are applied by a recurrence to the previous state of the electrical system the flowchart of Figure 4 clearly presents our study approach.

3.1. Voltage angles evolution

Figure 6 presents the voltages in each bus for the 13 cycles with the initial case for the fast decoupled method. Figure 7 presents the angles in each bus for the 13 cycles with the initial case for the fast decoupled method. Figure 8 presents the voltages in each bus for the 13 cycles with the initial case for the Gauss-seidel method. Figure 9 presents the angles in each bus for the 13 cycles with the initial case for the Gauss-seidel method.

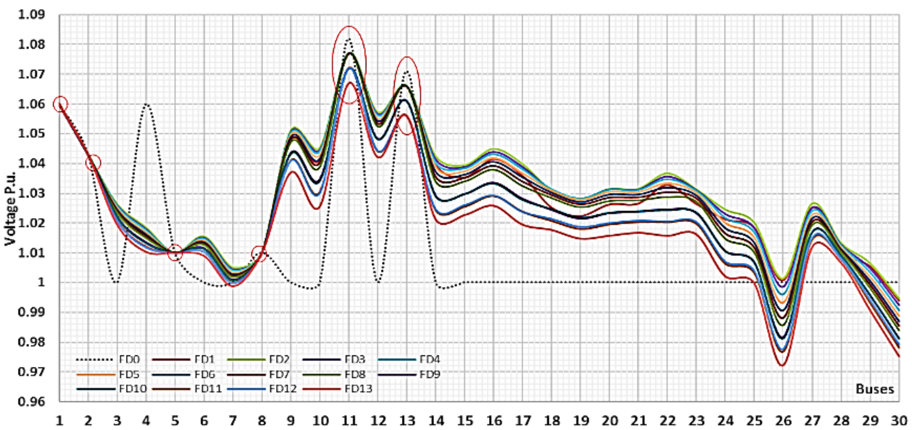

Figure 6. Voltage evolution (p.u.) for 13 cycles with the initial case (fast decoupled)

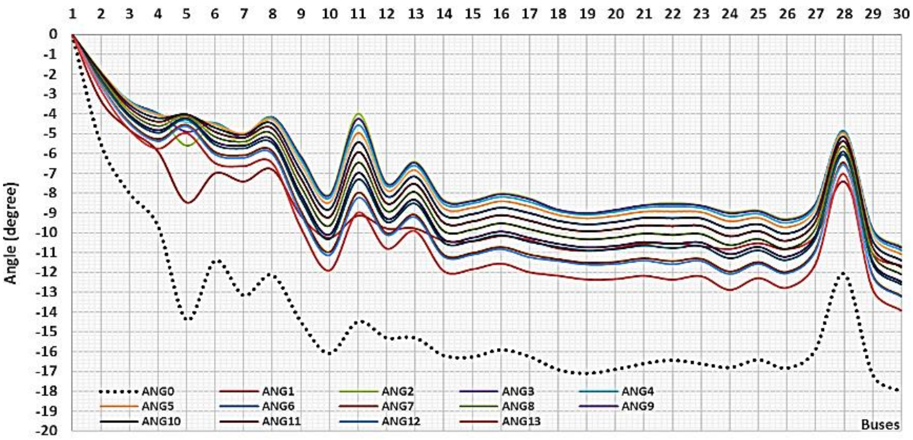

Figure 7. Angles evolution for 13 cycles with the initial case (fast decoupled)

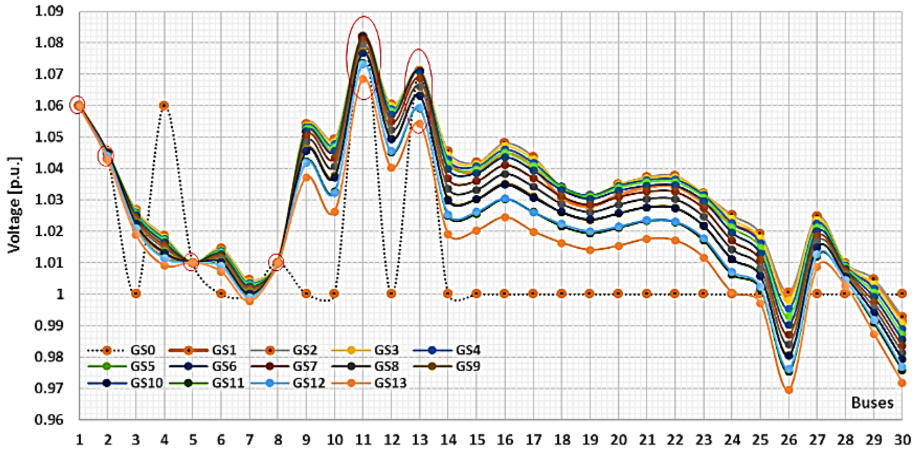

Figure 8. Voltage evolution (p.u.) for 13 cycles with the initial case (Gauss-seidel)

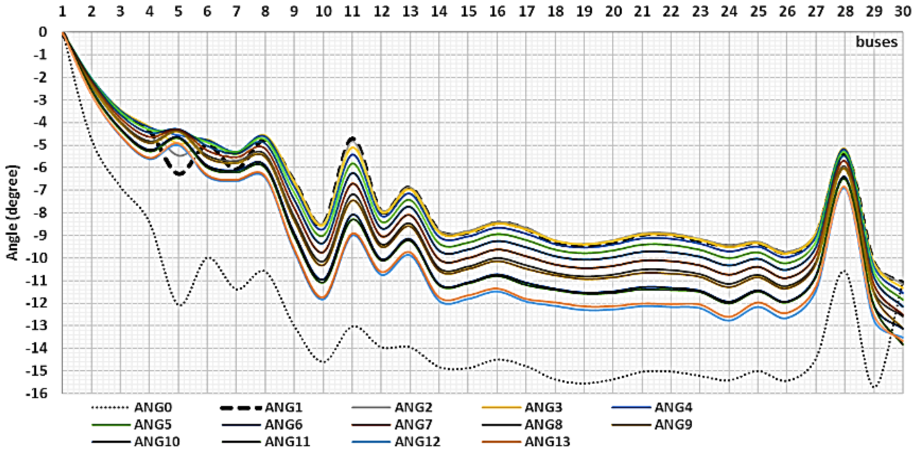

Figure 9. Angles evolution for 13 cycles with the initial case (Gauss-seidel)

4. DISCUSSIONS

According to the results of the tensions/angles that we found for the two methods, we notice that there is a decrease in the voltage planned for the two PV_bus 11 and 13, to therefore keep the reactive power within these limits, the controller degraded the voltage to values close to the planned voltages (1.07 and 1.08) compared to the initial case, for the 03 generators (Gen. 2, 5, and 08) the planned voltages remain in the initial value of the controller, so it does not there is no overshoot. We note that there are always two buses which have voltage drops but it does not exceed the lower limit. For the evolution of the angles, thanks to the decentralized productions and the stabilization of the small angles, there are remarkable improvements for the FD method compared to the GS, these results show that the controller kept the parameters of the system within the acceptable limits.

4.1. System frequency

During the course of 13 cycles, Figure 10 illustrates how the frequency and voltages in a power system can fluctuate in response to changes in the demand for electricity and the available supply. These variations are influenced by factors such as the system's load, generation capacity, and the way control mechanisms respond to these conditions. We note that the evolution of each load presents the same pace with deferent voltage values; it depends on the frequency of the system, which presents a variation of 0.02% of the initial value f_0.

4.2. Generator productions

In Figure 11 presents, the active power produced by each generator is carefully coordinated to meet the overall demand of the system while maintaining stability and reliability. Control mechanisms, such as automatic generation control (AGC) and economic dispatch, are employed to regulate the active power outputs of generators based on real-time demand and system conditions. The models of the total production plans of the six generators as well as the model of the dynamic loads with the production errors by the two Gauss-Seidel and Rapid Decoupled methods are presented in Figure 12. It can be seen that the total production entirely follows the variation of the total load demanded.

4.3. Iterations

The Figure 13 presents the iterations number for the both methods, Gauss-seidel and fast decoupled, are widely used for solving power flow problems in electrical power systems. They help determine the steady-state operating conditions, such as voltage magnitudes, angles, and power flows, under different load and generation scenarios.

4.4. Active losses of the system

Figure 14 presents the results of the total active losses of the system during the 13 cycles for the two methods. The calculation of total active losses involves analyzing the power flow and considering the resistance and impedance values of the various system components. Power flow analysis methods, such as the Gauss-seidel or fast decoupled method, can be used to determine the active losses in a power system.

The results obtained show that after each cycle the model of the losses follows the same model of the generator, the global active and reactive losses are reduced. By the control of the productions on the PV_buses (2, 5, 8, 11, and 13), the generators played an important role in the reduction of the total active losses compared to the initial case, this property is one of the advantages of decentralized production. According to the results of Figures 12, 13, and 14 it has been confirmed that the fast decoupled method is more efficient than Gauss-seidel for dynamic systems as well as the error between the productions and the loads is almost zero i.e., the system in the dynamic interval specified follows the load model fully taking into account the total losses, this dynamic robustness is interesting for the dispatching of complicated electrical systems in real time.

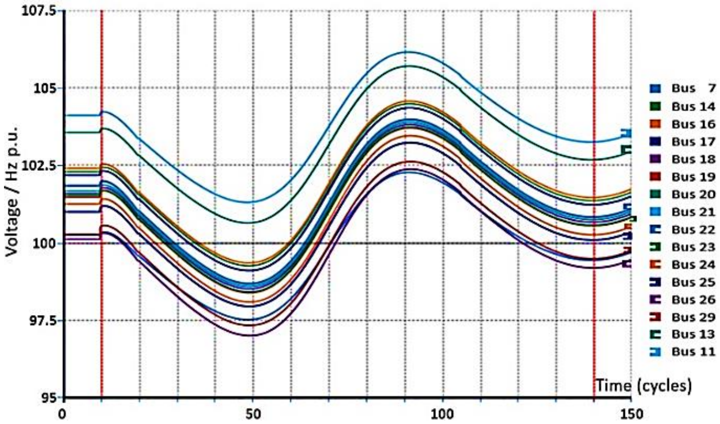

Figure 10. Actives powers evolution in PV buses generators for 13 cycles

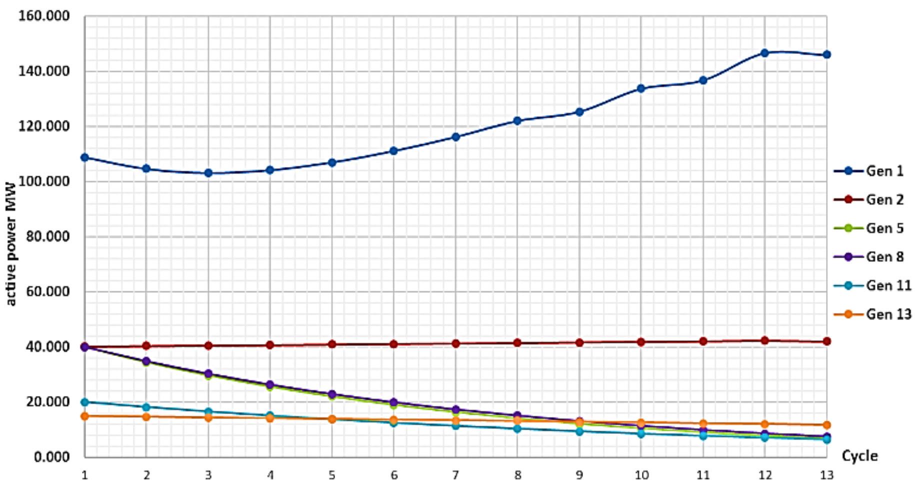

Figure 11. Actives powers evolution in PV buses generators for 13 cycles

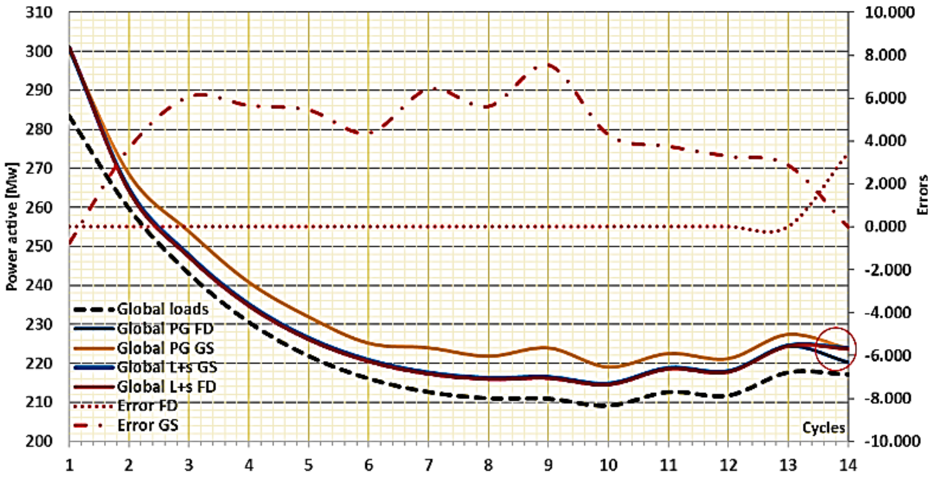

Figure 12. Power Active generations in GS and FD methods with global loads model and errors

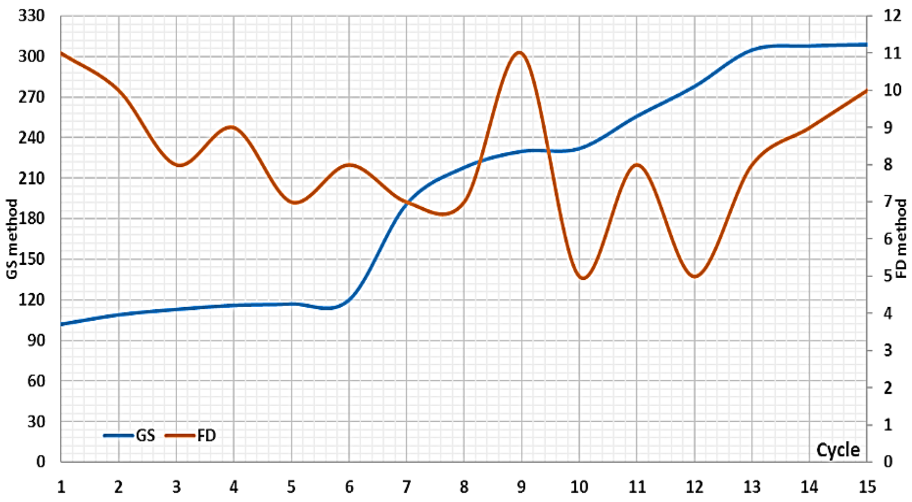

Figure 13. Number of iterations by fast decoupled and Gauss Seidel methods

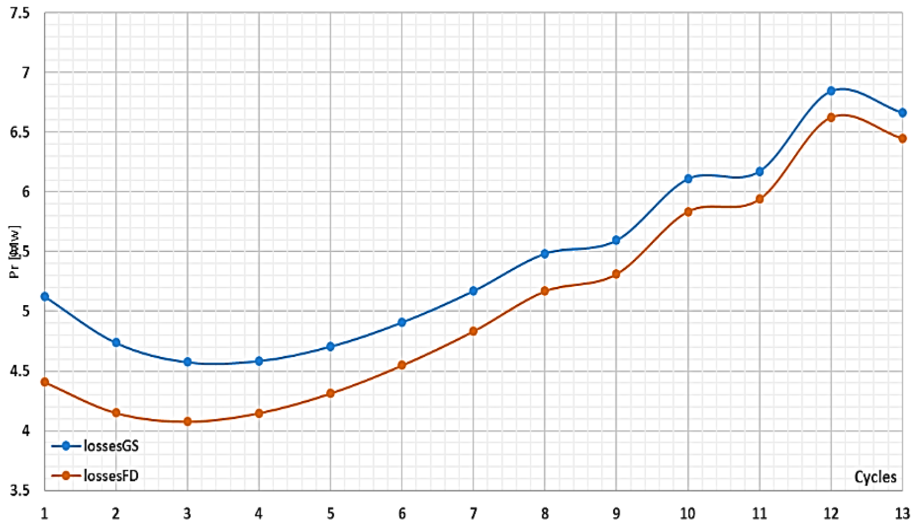

Figure 14. Global active power losses for 13 cycles of both methods

5. CONCLUSION

Our undertaking involves the development of a program that can compute and juxtapose the dynamic efficiency of generators based on different load conditions observed over 13 real-time monitoring cycles. Our findings imply that building a model of the electricity production system is indispensable for efficacious power dispatching, regardless of whether the controls used are conventional or intelligent. This study furnishes valuable insights for dispatchers as it empowers them to prophesize the network's state and devise electrical production plans based on technical and economic factors, chiefly in the context of dynamic loads, which provide innumerable opportunities for power gratification. The outcomes we have procured proffer a persuasive opportunity for us to apply this study on a genuine network with greater complexity. Hence, we are prompted to embark on other dynamic studies that utilize artificial intelligence. We acknowledge that whilst some dynamic strains of electrical loads can be modeled in a linear manner, others necessitate more intricate methods to extract the model from the control.

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