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Power system stability improvement using fuzzy logic FACTS-UPQC conditioner

Emmanuel Lenjo[1], Pierre Kenfack[1,2], Jean Maurice Nyobe Yome[1]
[1]Laboratory of Computer Science Engineering and Automation, University of Douala, Douala, Cameroon
[2]College of Technology, University of Buea, Buea, Cameroon

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ABSTRACT

In power system, stability analysis becomes important to identify the level of stability and security of electrical power systems. This article proposes a flexible alternating current systems-unified power flow compensator (FACTS-UPQC) compensator installed in the high-voltage network to ensure stability of voltage and frequency in the power grid facing voltage dips, over-voltage and short-circuit faults. Thus, an artificial intelligence algorithm based on fuzzy logic method is implemented to have the appropriate values of FACTS-UPQC conditioner. The voltage stability improvement is demonstrated by the variation margin of amplitude and phase angle. Frequency stability aims to obtain a frequency within a minimal variation. A 14-bus test electrical system is modeled to implement the advanced control strategy. MATLAB/Simulink software is used to prove the functionality of the method in improving the stability of power system. The simulation results showed a reduction of harmonic distortion rate (HDR) and a minimization of the voltage variation range for the implemented fuzzy logic system compared with the literature.

Corresponding Author:

Emmanuel Lenjo
Laboratory of Computer Science Engineering and Automation, University of Douala
Douala, Cameroon
Email: emmanuellenjo201@gmail.com

1. INTRODUCTION

The growth of the world population and the consumption of electrical energy urged electrical energy companies to choose alternative sources using renewable energy [1]. Thus, the current power networks face several constraints, namely: line voltage instability, transformer overload, the start-up of thermal power stations favoring the unwanted increase in energy losses and operating costs of electrical power networks [2]. Establishing efficient connections of electrical power systems would improve quality of electrical energy, ensure the stability of operation of the electrical grid and promote rapid development of the global economy. Flexible alternating current systems (FACTS) systems considered as intelligent devices made up of power electronic switches such as thyristors, are used to improve the static and dynamic stabilities of voltage profile in power networks [3]. Furthermore, the optimization of the design parameters of FACTS systems has shown crucial importance for improving the stability control of the power systems. Several advanced computing techniques are proposed in the literature for FACTS system design, namely firefly optimization algorithm (FOA), cuckoo opposition algorithm (COA), bacteria algorithm (BFA), and ant colony optimization algorithm (ACO) [4].

2. RELATED WORKS

Recently, flexible alternating current systems-unified power flow compensator (FACT-UPQC) controllers based on artificial intelligence and fuzzy logic methods have been developed in the literature in order to consider the non-linearity of compensator parameters. Work in [5] proposed a new approach to simultaneously improve power stabilizers and FACTS controllers for enhancement of the electrical power network stability by considering time delays. Zadehbagheri *et al.* [6] proposed to optimally place FACTS to improve the electricity grid stability under different conditions. Basu *et al.* [7] proposed a new control technique using FACTS-UPQC devices. Works in [8] presented a review of FACTS-UPQC to enhance transmission system. Moreover, many researches have been studied and classified to prove the effectiveness of the proposed compensator. Nagarajan *et al.* [9] explored a study of power quality problems. Chen *et al.* [10] described the theory and modelling of FACTS-UPQC devices. Agarwal *et al.* [11] proposed a literature overview on FACTS-UPQC. Yasmeena and Das [12] developed a FACTS-UPQC device combining shunt and series compensator. A general review of the literature is given in Table 1.

Table 1. General review of literature

Author	Problem	Method	Test network	Results	Perspectives
[13]	Analysis of the stability of electrical power systems	Newton-Raphson method	IEEE 14-bus test network	Frequency = 58.3 Hz	Determine the charging and discharging times
[14]	Analyzing the impedance characteristics of voltage converters and distributed generation	Impedance model	Isolated microgrid	Frequency oscillation=5.879 Hz	Consider the impact of isolated detection
[15]	Analyzing the stability of an electrical power network	SVM, KNN, LR, DT, RF	IEEE 14-node network	F1 score= 91.1% and 99.2%	Carry out an in-depth study of prediction damping rate
[16]	Time series trajectories prediction of system	Deep neural network	IEEE 39 and 300 bus networks	Accuracy= 98.93% and 96.84%	Ameliorate the transient stability
[17]	Stability of power systems	Large scale scheme based on PMUs	IEEE 39-bus network	Voltage= 0.8 and 1.2 pu	Improve the voltage magnitude
[18]	Stability of an electrical power network facing unknown attacks	Continuous-time Model predictive control (MPC)	Real Taiwan network	Frequency=59.65 Hz	Implement a predictive model
[19]	Improving the stability of the electrical power systems	Optimization algorithm	39 New England buses	Time= 150 ms and of 450 ms	Integration of renewable sources
[20]	Analysis of the transient stability of a multi-machine electrical network	Artificial intelligence	IEEE 68 bus network	Frequency= 59.63 Hz	Improve the critical time of the electrical system
[21]	Stability classification in a power grid	Multi-objective feature selection function	IEEE 39 bus network	Accuracy = 95.6%	Improve the performance of the classifier
[22]	Improve the stability of electrical networks	Adaptive neuro-fuzzy algorithm	IEEE 34 node network	Precision= 96.4%	Improve the performance indices

Based on previous works, this article proposes a novel power systems compensation scheme based on a FACTS-UPQC stabilizer controlled by fuzzy logic algorithm to reduce oscillations and disturbances on electrical power network stability by identifying the key values of the compensator. The effectiveness of the implemented strategy is compared with the most used algorithms in literature such as PSO and GA. The contributions of this study are presented as follow:

- A new scheme of a FACTS-UPQC compensator based on a fuzzy logic algorithm is proposed in this article to improve the electrical network stability.
- Additionally, the parameters of fuzzy logic controller are optimally chosen from an objective function.
- The FACTS-UPQC controller based on a proposed fuzzy logic algorithm is compared to other classical algorithms in the literature such as PSO and GA in terms of voltage amplitude, harmonic distortion rate (HDR) and frequency stability.
- Several disturbance scenarios were implemented and simulated such as short-circuit faults and voltage sags in a 14-node test network to show the outperformance of the proposed FACTS-UPQC controller.

This work is structured as follows: section 3 gives the methodology. For this purpose, the test electrical network is presented as well as the simulation software used. Furthermore, the control technique based on fuzzy logic is presented along with the FACTS-UPQC conditioner. Section 4 gives the results and discussion. Conclusion and future works are presented in section 5.

3. METHOD
3.1. Material
3.1.1. Test electrical network

In this article, we modeled a portion of Cameroonian electrical network to test our fuzzy logic controller. This portion of the network is composed of 14 buses, two transformers, two high voltage lines and several loads connected through electrical transmission lines as shown in Figure 1. The loads and shunt capacitors are considered to be connected to the bus 5, 9, 11, 13, and 14. The 05 zones are connected through 10 km line, 6 km, and 12 km line. The loads are characterized by a constant total impedance. The power transmitted in the line is 10 MW. The electrical system is capable of reacting to the appearance of any fault or disturbance.

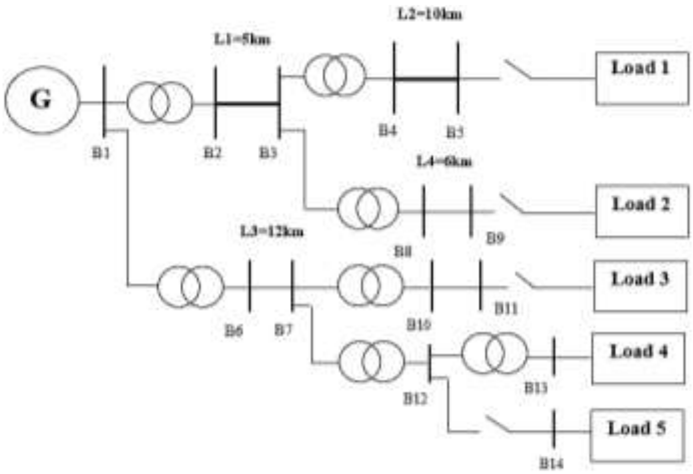


Figure 1. Test electrical network

3.1.2. Experimental setup

The experimental setup is made of MATLAB version 2021 with a Lenovo computer I-Core 7 with a 3 GHz processor, 8 GB of RAM, 1 Terabit of hard disk, Windows 10/64 bit system. In this work, MATLAB has shown its efficiency and precision in the simulation of dynamic electrical systems by providing a powerful protection system for the management of the electrical network through powerful and rich calculation functions.

3.2. Method
3.2.1. Fuzzy logic
a. Overview of fuzzy logic

The premises of fuzzy logic appeared before the 1940s, with the first studies of uncertainty concept by American researchers. It was not until 1965 that the concept of fuzzy subsets was proposed by L. A. ZADEH, an internationally renowned automation scientist, professor at the University of Berkeley in California, who contributed to the modeling of phenomena in fuzzy form, with a view to overcome the limitations due to the uncertainties of classical differential equation models [23], [24]. Fuzzy logic is an approach used in artificial intelligence based on "values or degrees of truth" in the form of real numbers between 0 and 1 [25].

Fuzzy logic controller consists of the following elements:
- Linguistic variables: they are words or sentences expressed in human language, the description of a certain situation, a phenomenon or a process generally contains vague expressions (some, often, hot, cold, fast, slow, big, and small).
- Fuzzy sets: they are defined on a universe of discourse represented by:

$$A = \{(t, \mu_A)/t \in U\} \tag{1}$$

when U is continuous, the fuzzy set A is represented by:

$$A = \int t\mu_A(t) \tag{2}$$

when U is discrete, A is represented by:

$$A = \sum \mu_A (ti)/ti \quad (3)$$

- Membership functions: they characterize each linguistic value. They can be numerical and functional. Some standard forms of membership functions are commonly used to represent discourse-based fuzzy sets.

b. Structure of fuzzy logic controller

A fuzzy system can be interpreted from two methods: mathematical or logical. From a mathematical method, a fuzzy system is a non-linear function relating an input data vector to an output vector and, from a logical method, a fuzzy system is a decision-making system, based special knowledge composed of four main modules, namely: the rule base, fuzzification, inference engine and defuzzification. The fuzzy regulator is only a special case of fuzzy systems intended to calculate the control. The structure of a fuzzy controller is given in Figure 2.

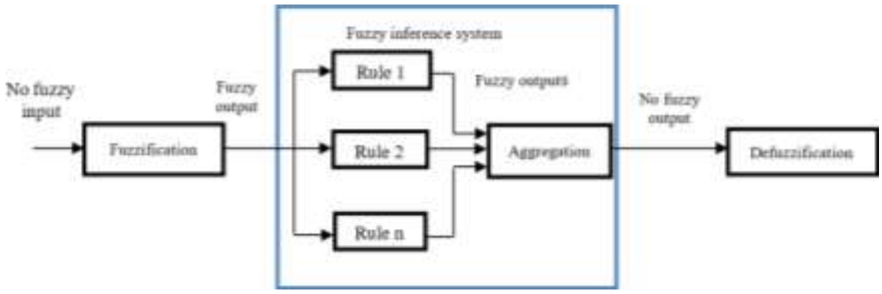


Figure 2. Structure of a fuzzy controller

This controller works as follows:
- Fuzzification: fuzzification consists of assigning to the numerical value of each input, at time t, its function of belonging to each of the previously defined classes.
- Fuzzy rules: the main idea is to express human knowledge in the form of fuzzy rules describing the behavior of the system with the form If… Then….
- Aggregation of rules: depending on the type of implication, the operator uses conjunctive or disjunctive rules to aggregate. Thus, in command, the implication generally being of the conjunctive type, this amounts to considering that the rules are linked by 'AND' or 'OR' operator.
- Inferences: they are used to measure quantities and the output variables by linguistic rules which are combined using the connections (and) and (or). These rules will make it possible to move from a degree of belonging to an input or controlling quantity to the degree of belonging to an output or command quantity.
- Defuzzification: defuzzification is the final step, this step performs the reverse operation of fuzzification. In fact, this involves calculating a numerical value that can be understood by the external environment based on a fuzzy definition. Several methods exist and allow you to find an output value: the maximum method, the maximum barycenter method and the gravity center method. The most used method is the "gravity center" or "centroid" method.

3.2.2. FACTS-UPQC compensator

Based on literature studies which were able to validate both parallel and series active power filters (APF). However, each of the two filter structures only supported one type of disturbance (current or voltage), which led us to establish a study on a universal structure, in developing of a power conditioner. For our system, we opted for the instantaneous power p-q method for the identification of both the reference currents and reference voltages for the parallel and series active filter for a non-linear load. In order to compensate all current and/or voltage disturbances, we isolated the source side from disturbances generated on the load side. Figures 3 and 4 respectively show the general structure of the UPQC conditioner and the flowchart of our method.

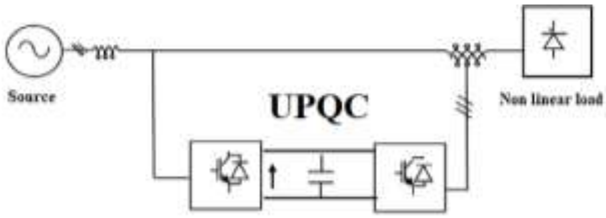


Figure 3. General structure of the UPQC conditioner

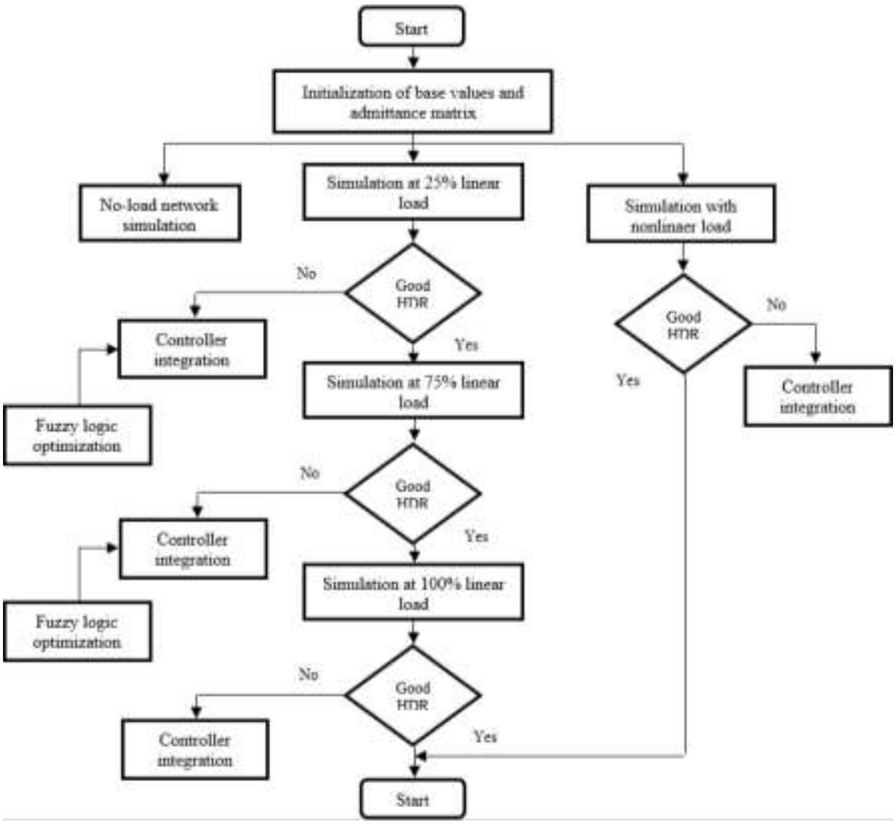


Figure 4. Flowchart of our method

As shown in Figure 3, the general structure of this system contains the following components:
- Two inverters: connected on the load which works as an APF.
- The L_{fp} parallel coupling inductor used to connect the parallel inverter to the grid. It helps to smooth the shape of the current wave.
- A common DC continuous source, which interconnects the two inverters and also keeps the V_{dc} voltage across its constant.

As shown in Figure 4, we start by initialization of base values and admittance matrix. Then, we can perform either no-load network simulation, simulation at 25% linear load or simulation with nonlinear load. In case of simulation at 25% linear load, we verify the HDR. If the HDR is good, we perform simulation at 75% linear load and we also check the HDR, else we integrate controller by fuzzy logic optimization. Then, we perform simulation at 100% linear load, if the HDR is good, we end the process, else we integrate the controller by fuzzy logic optimization.

4. RESULTS AND DISCUSSION

For this part, our objective is to eliminate voltage type disturbances on the load side created by disturbed currents which are generated because of a load represented by a diode rectifier bridge on a load represented by a circuit. The power system parameters can be seen in Table 2 which is tested in MATLAB software.

Table 2. Parameters of the test electrical network

Elements	Parameters	Unite	Value
Source	Voltage level	kV	25
	Resistance	mΩ	2.55
	Inductance	µH	65.24
	Frequency	Hz	50
Transmission system	Length	km	10
	Resistance	mΩ/km	3.85
	Inductance	µH/km	35.62
Load	Resistance	Ω	1.55
	Inductance	µH	4.95
DC-DC converter	Voltage level	V	500
Inverter	Nominal maximum voltage	V	400
	Efficiency	%	95
3-phase transformer	Power	kVA	250
	Primary voltage	kV	25
	Secondary voltage	V	400

Figure 5 shows the simulation model of the electrical network with the UPQC conditioner. This system represents the interconnection of UPQC technology with electrical power system. To emphasize, the electrical power system simulation consists of representative 25 kV distribution system feeders. A three-phase voltage stability control allows sustain unity for power flow purposes. Figure 6 gives the results of the source current, the load current and the filter current for the two simulation cases Figure 6(a) without and Figure 6(b) with compensator. Table 3 gives a comparison of the HDR for the simulation cases without compensator and with compensator. Three types of disturbances are investigated, including overvoltage, voltage sag, and short circuit fault. In each scenario, the system without conditioner and without conditioner are compared.

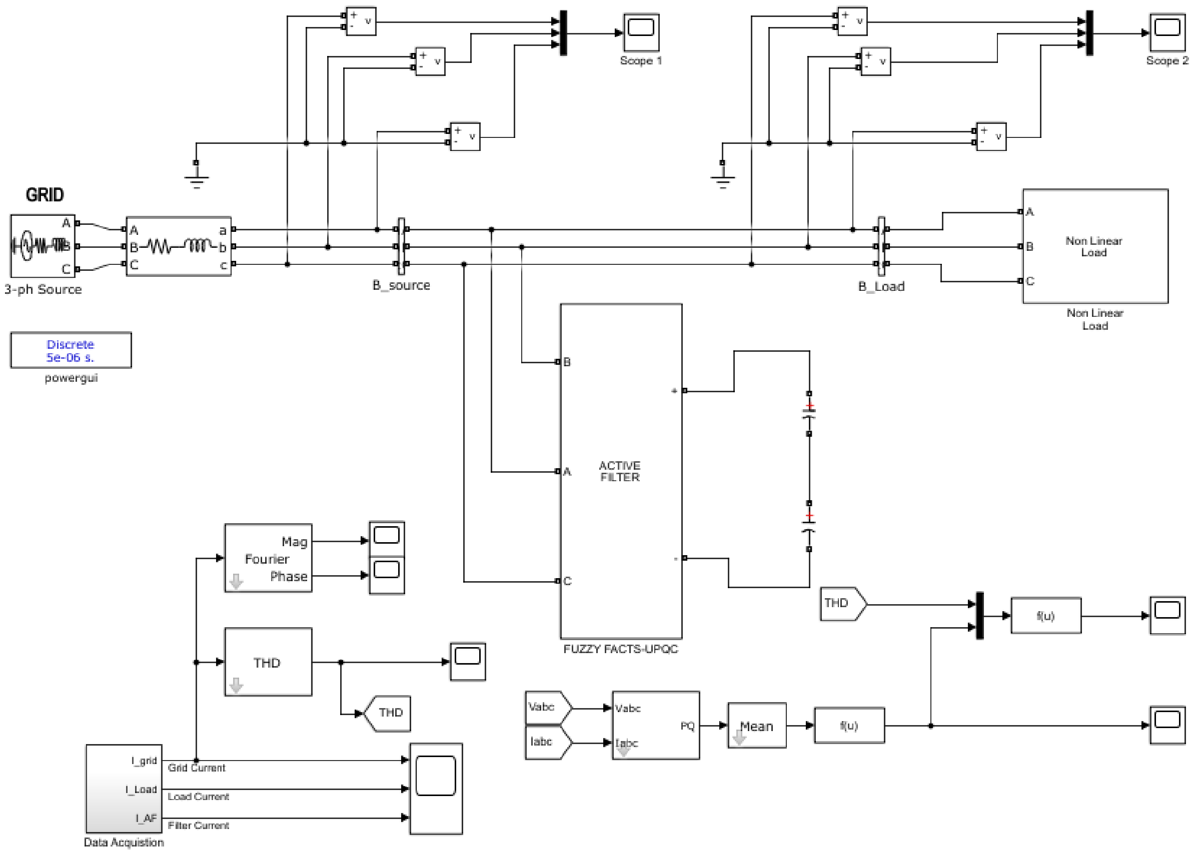
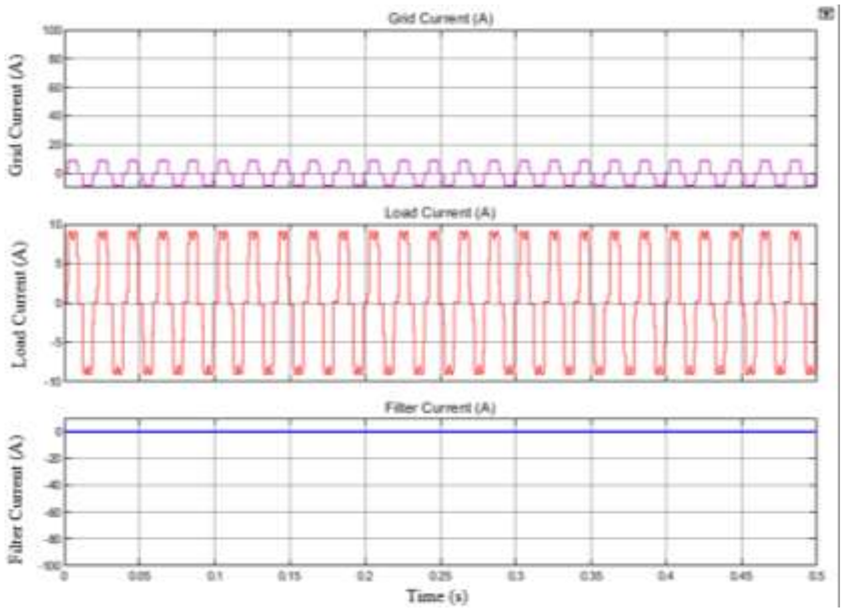
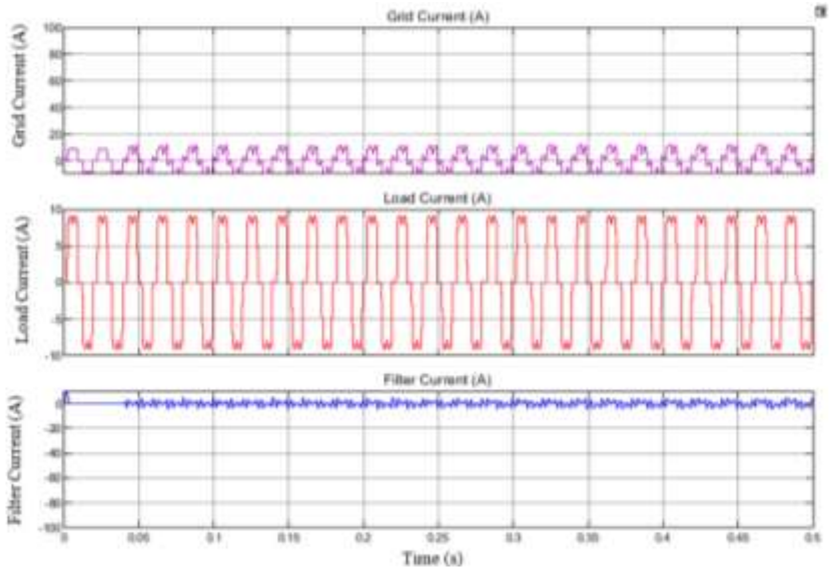


Figure 5. Simulation model of power system with active UPQC compensator



(a)



(b)

Figure 6. Grid current, load current, and filter current (a) without compensator and (b) with compensator

Table 3. Comparison of the HDR

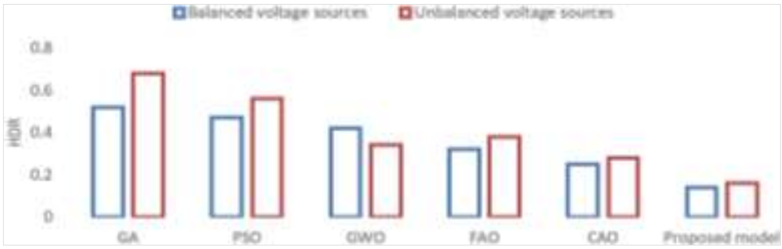
Case	GV	LV	GC	LC	FC
Without compensator	0.249	0.249	0.4807	0.3426	$1.49*10^{-8}$
With compensator	0.124	0.124	0.3426	0.3414	1.113

This filter allows a reduction of current harmonics. The HDR value is reduced to 50.2% after filtering. We notice that the active parallel power filter eliminates current harmonics very well. This filter allows a reduction of current harmonics for the three phases. The HDR value is reduced after filtering. We notice that the active parallel power filter eliminates current harmonics very well and makes them more balanced. Table 4 summarized the comparison with the literature of optimization techniques of power networks in terms of voltage stability (VS), frequency stability (FS), and transient stability (TS).

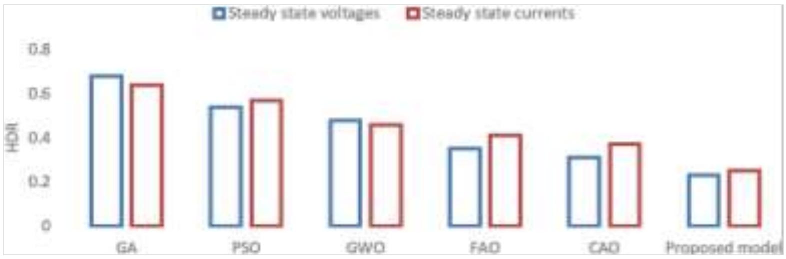
Table 4. Comparison with the literature

Method	VS	FS	TS
Meta-heuristic optimization algorithm [5]	21%	33%	53%
GA [6]	54%	34%	53%
Nonlinear discrete-time model [10]	59%	47%	66%
PSO-based multi-objective planning algorithm [14]	63%	62%	61%
PSO-based neural networks [17]	74%	61%	63%
Rider optimization algorithm based modified PSO [19]	83%	77%	89%
Proposed model	96%	98%	97%

As shown in Table 4, the proposed method gives better simulation results compared with those in the literature. The proposed control strategy gives a voltage stability rate, frequency stability rate and transient stability respectively 96%, 98%, and 97%. The voltage stability, the frequency stability and the transient stability are better with the proposed model using the FACTS-UPQC conditioner. These results are explained with the great capacity of the FACTS-UPQC in the correction of HDR of the electrical power network. This result is shown with the optimization of the HDR and the stabilization of the voltage and frequency by the introduction of an intelligent algorithm. Moreover, the proposed hybrid controller used a series APF associated with fuzzy logic controller allowing an optimization of the stability performance in the power grid. This model allowed an extra-ordinary performance in terms of diminishing total harmonics distortion, and voltage distortions are reduced. Figure 7 gives the comparison with the literature of HDR. Then, Figure 7(a) demonstrated the comparison with the literature of HDR under balanced voltage sources and unbalanced voltage sources. Figure 7(b) gives the comparison with the literature of HDR under steady state voltages and steady state currents. Figure 7(c) demonstrated the comparison with the literature of HDR under balanced loads and unbalanced loads.



(a)



(b)

(c)

Figure 7. Comparison with the literature of HDR: (a) under balanced voltage sources and unbalanced voltage sources, (b) under steady state voltages and steady state currents, and (c) under balanced loads and unbalanced loads

It can be seen that the simultaneous use of power system stabilizer and fuzzy logic algorithm has better results than GA, PSO, GWO or FAO algorithm in damping oscillation. The new stabilizer compared to the GA creates 64% reduction in the maximum overshoot and 80% reduction in distortion rate and compared to the PSO creates 53% reduction in the maximum overshoot and 39% reduction in distortion rate. As shown in these results, it can be observed that the HDR is better with the application of the proposed hybrid algorithm compared with other methods of the literature.

5. CONCLUSION

This paper proposed a new FACTS-UPQC compensator in the electrical grid to improve the stability during a disturbance, short circuit fault or overload. To this end, we proposed a machine learning method allowing the identification of the optimal parameters of the UPQC conditioner based on fuzzy logic controller. The proposed method was implemented in a 14-node test electrical network with a nonlinear load. In addition, the MATLAB/Simulink software allowed us to model this test network with the FACTS-UPQC conditioner based on fuzzy logic controller. The simulation gives a reduction in the HDR of around 50.2% for the load current. These results demonstrated the effectiveness of FACTS-UPQC conditioner for improving the stability of the electrical network compared to the series and parallel compensators in the literature. This work can be extended for the control of a large-scale electrical network to prevent any disturbance. Additionally, novel hybrid optimization techniques can be implemented to enhance the functionality of a future larger system.

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BIOGRAPHIES OF AUTHORS

Mr. Emmanuel Lenjo is a Ph.D. student at university of Douala. His interests include electrical transportation, power system, electrical compensation and stability analysis. He can be contacted at email: emmanuellenjo201@gmail.com.

Prof. Pierre Kenfack is an associated professor at University of Buea. He is the former head of department at ENSET of University of Buea. His research interests include electrical transportation, optimization of power system, smart grid, electrical compensation and stability analysis. He published more than 15 articles in international journals. He can be contacted at email: pierrekenfack2003@yahoo.fr.

Prof. Jean Maurice Nyobe Yome is an associated professor at university of Douala. He is also the deputy director of polytechnic of Douala. He published more than 20 articles in international journals. His interests include power systems, power electronics, smart systems and electrical conversion. He can be contacted at email: nyobeyome@yahoo.fr.