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Voltage regulation using three phase electric spring by fuzzy logic controller

Introduction. *The renewable energy sources such as solar and wind power have increased significantly in recent years. However, as the generation of renewable energy has become more integrated, its intermission and instability have a major impact on the power system's stability, such as voltage instability and frequency flicker.* ***Purpose****. In order to address the different power quality issues brought on by intermittent and unreliable renewable energy sources, electric spring offers a novel solution. It was proposed as a technique for regulating load and adjusting output power. For the integration of electric springs with noncritical loads, a contemporary control mechanism is described in this paper.* ***Novelty.*** *The suggested work is innovative in that it presents an improved control technique that efficiently maintains voltage stability as voltage changes.* ***Method.*** *The proposed technique is based on an analysis of the initial conditions and input data for developing fuzzy rules for calculating compensating voltages in relation to the difficulties.* ***Results.*** *This suggested fuzzy controller will be able to maintain the regular operation of the electric spring of power output control stability as well as continuing to provide power factor improvement and voltage control for significant loads, including the home's protection system.* ***Practical value.*** *A detailed study of typical voltage regulation is undertaken, supported by simulation results, to demonstrate the effectiveness of the applied control scheme in cancelling the corresponding issues with power quality.* References 25, tables 2, figures 8.

Key words: **voltage stability, fuzzy control, electric spring, power factor, microgrid, renewable energy sources.**

Вступ*. Відновлювані джерела енергії, такі як сонячна та вітрова енергія, значно збільшилися останніми роками. Однак у міру того, як виробництво відновлюваної енергії стало більш інтегрованим, його перебої та нестабільність впливають на стабільність енергосистеми, наприклад, нестабільність напруги та коливання частоти.* ***Мета****. Щоб вирішити різні проблеми з якістю електроенергії, викликані уривчастими та ненадійними відновлюваними джерелами енергії, електрична пружина пропонує нове рішення. Вона була запропонована як метод регулювання навантаження та регулювання вихідної потужності. Для інтеграції електричних пружин із некритичними навантаженнями у цій статті описано сучасний механізм керування.* ***Новизна****. Пропонована робота є новаторською, оскільки представляє вдосконалений метод управління, який ефективно підтримує стабільність напруги за зміни напруги.* ***Метод****. Запропонована методика заснована на аналізі початкових умов і вихідних даних для розробки нечітких правил розрахунку компенсуючих напруг стосовно труднощів.* ***Результати****. Пропонований нечіткий регулятор зможе підтримувати стабільну роботу електричної пружини контролю вихідної потужності, а також продовжувати забезпечувати покращення коефіцієнта потужності та контроль напруги для значних навантажень, включаючи систему захисту будинку.* ***Практична цінність****. Зроблено докладне дослідження типового регулювання напруги, підтверджене результатами моделювання, щоб продемонструвати ефективність схеми управління, що застосовується в усуненні відповідних проблем з якістю електроенергії.* Бібл. 25, табл. 2, рис. 8.

Ключові слова: **стабільність напруги, нечітке управління, електрична пружина, коефіцієнт потужності, мікромережа, відновлювані джерела енергії.**

Introduction. The electricity systems are now incorporating the «Smart Grid» idea, which makes the grid smarter by enabling two-way energy flow between the grid and the consumer. One aspect of the smart grid concept is the integration of renewable energy sources (RES). The system should incorporate major RES's due to the impending energy problem as well as environmental considerations. Solar energy is the most important RES since it is neat, unrestricted, and free. Production of electrical energy in conventional systems is dependent on load demand [1]. In addition, solar energy is infrequent and longwinded. As a result, the emphasis has shifted from source following load to load following source, creating a new paradigm for electric springs (ES). Contrarily, solar photovoltaic (PV) systems produce a low output that is increased by converters and then transformed by inverters for grid synchronization into a pure sinusoidal form. The entire PV system performs at peak efficiency and generates its maximum output power at a certain location on the voltage-current (*V*-*I*) or voltage-power (*V*-*P*) curve known as maximum power point (MPP) at varied irradiance and temperatures. The MPP can be monitored using a number of methods. Through the use of maximum power point tracking (MPPT) techniques, the operating point of the PV array is kept at MPP [2, 3].

The power imbalances, voltage instability, voltage swings, and other grid-related problems are all being brought on by solar grid integration. These power quality issues have been addressed using a variety of technologies, including capacitor banks, capacitor reactors, static compensators, and static synchronous series compensators.

Their rapid and dynamic controllers can effectively minimise problems with power quality. The literature claims that ES outperforms existing technologies in dealing with the aforementioned problems [4-6]. This study emphasises the practical integration of a PV system with the grid. The ES is a fast device that controls voltage across significant loads that are prone to voltage variations. A power electronics-based circuit called ES is based on the idea of applying Hook's law to the field of electricity. The ES differs from typical custom power devices in terms of the better voltage profile of the power system. On the load demand side, ES is utilised to stabilise voltage variations brought on by RES.

The ES is a highly dynamic low-cost current control voltage source device [7-10]. The ES is connected in cascade with a noncritical load (NCL) that is less susceptible to voltage fluctuations in order to create a smart load. In order to achieve voltage regulation across the critical load (CL), which is voltage sensitive, the ES creates the compensation voltage or ES voltage V_{ES} perpendicular to the noncritical load current I_{ES}. In the past, simulations were used to research how well ESs worked in the real world. The works [11, 12] discuss the implications of large-scale integration of renewable energy sources, such as PV, into the grid and its consequences [13-16].

The goal of the paper is to design controller for electric spring to regulate voltage and which allows to increase the reliability of the entire system mechanism operation and significantly simplify the design.

Subject of investigations. This paper carries out a comprehensive study of the ES and understanding of the different parameters to design suitable controller for voltage stability in the system under different environmental condition. This paper gives idea about the behavior of ES as capacitive mode and inductive mode.

Basic calculation relationships and assumptions. By comparing ES to a conventional mechanical spring, the concept was first established [17, 18]. It might be implemented using an inverter and connected in series with noncritical loads like electric heaters, refrigerators, and air conditioners in a RES-powered microgrid, as shown in Fig. 1. This creates a smart load. A building's security system is connected in parallel with this smart load, as are other critical loads. An input-voltage control method was used in earlier iterations of ES to produce reactive power compensation and offer steady-state voltage and power regulation to important loads because RESs only produce power intermittently, the noncritical load voltage and power fluctuate in response to grid fluctuation.

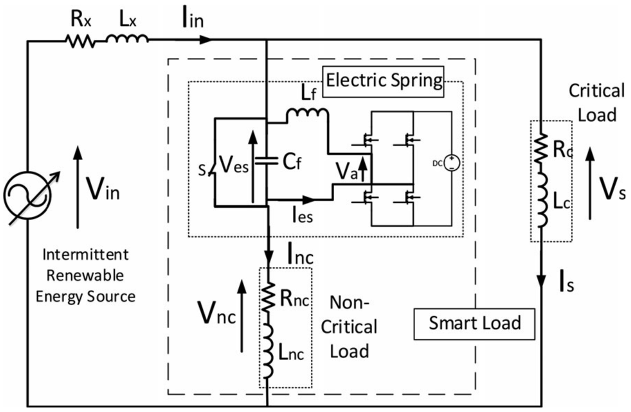

Fig. 1. Structure of ES

The compensation voltage, or ES voltage, V_{es}, should be perpendicular to the noncritical load current, I_{nc}, in order for the ES to exclusively offer reactive power adjustment, where V_s is the line voltage, V_{nc} is the noncritical load voltage, and V_{es} is the ES voltage, governs the ES voltage. A significant reactive power injection can degrade the system's power factor and lower power efficiency in a distribution system with a variety of inductive and capacitive loads.

$$V_{nc} + V_{es} = V_s . \quad (1)$$

Thus, in addition to the current qualities of voltage and power regulation, a power factor correction (PFC) function can be added to the ES. The both active and reactive power correction could be provided from an ES by using a DC source, like a battery, to power the inverter, as shown in Fig. 1. The line current, I_{in}, might be shaped to be in phase with the line voltage, V_s, using this characteristic of an ES. In a system with resistive-inductive loads, or one that has a generally trailing power factor, the phasor diagram in Fig. 2 demonstrates the ES compensation voltage, *Ves*, could help increase the power factor in the distribution system and offer voltage and power support in steady state [19].

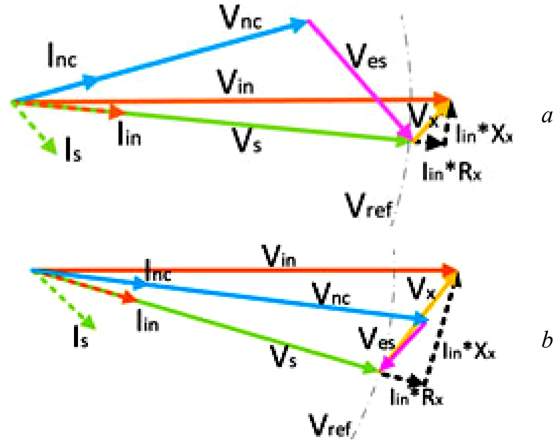

Fig. 2. Phasor diagram of current and voltage for PFC: *a*) undervoltage; *b*) overvoltage

When the line voltage V_s is less than the reference line voltage V_{ref} 230 V is the root mean square (RMS) value this is referred to as the undervoltage case. When the line voltage is higher than the reference line voltage, this is referred to as the overvoltage situation. As seen in Fig. 2,*a*, the ES injects real and capacitive power into the system in the undervoltage situation to raise the line voltage V_s to the reference value of 230 V and maintain the phase of the line voltage V_s and line current I_{in}. According to Fig. 2,*b*, the overvoltage scenario, for similar tasks to line voltage control and PFC, the ES injects a mix of actual and inductive power into the system. The input voltage, voltage across the line impedance, line voltage, noncritical load voltage, and ES voltage are represented in Fig. 2 by V_{in}, V_x, V_s, V_{nc}, and V_{es} respectively. The critical load current, noncritical load current, and line current are represented by I_s, I_{nc}, and I_{in} respectively. Additionally, $R_x + jX_x$ is the power circuit's line impedance, where R_x is resistance, $X_x + L_x$ and L_x is the line inductance.

Basic control action in fuzzy logic control (FLC) is governed by a set of linguistic rules. These rules are set by the system. Since numerical variables in FLC are converted to verbal variables, mathematical modelling of the system is not required. The FLC is divided into three sections: fuzzification, interference engine, and defuzzification [20]. The FLC is specified as 7 fuzzy sets for each input and output. Triangular membership functions are employed for simplicity. Fuzzification by the utilisation of an endless universe of discourse, Mamdani's «min» operator is used to imply implications. Defuzzification uses the height technique.

Fuzzification. The 7 fuzzy subsets used to assign membership function values to the linguistic variables are NB (Negative Big), NM (Negative Medium), NS (Negative Small), Z (Zero), PS (Positive Small), PM (Positive Medium), and PB (Positive Big). The partition of fuzzy subsets and the membership change in error *CE*(*k*), error *E*(*k*) function's shape adjust the form to the proper system. The value of input error and the change in error are standardised using an input scaling factor. The membership function plot of these variables is shown in Fig. 3.

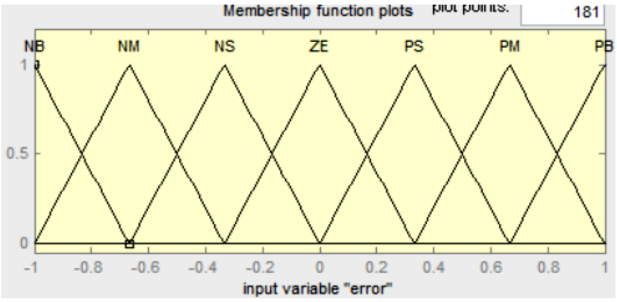

Fig. 3. Fuzzy membership function

This system's input scaling factor was constructed so that input values fall between –1 and +1. This arrangement's membership function has a triangular shape, which suggests that there is only one dominant fuzzy subset for each given $E(k)$ input [21, 22]. The input error for the FLC is as follows.

Inference approach. The max-min and max-dot are two composition approaches that have been put out in the literature. In this study, the min method is used. The output membership function of each rule is determined by the minimum and maximum operators. Table 1 displays the FLC's governing framework.

Table 1

Fuzzy rules

Change in error	Error						
	NB	NM	NS	Z	PS	PM	PB
NB	PB	PB	PB	PM	PM	PS	Z
NM	PB	PB	PM	PM	PS	Z	Z
NS	PB	PM	PS	PS	Z	NM	NB
Z	PB	PM	PS	Z	NS	NM	NB
PS	PM	PS	Z	NS	NM	NB	NB
PM	PS	Z	NS	NM	NM	NB	NB
PB	Z	NS	NM	NM	NB	NB	NB

Defuzzification. Since most plants require a nonfuzzy control value, a defuzzification stage is necessary. The FLC output is calculated using the «height technique» and the FLC output has an impact on the control output. The FLC output also manages the switch on the inverter. It is necessary to maintain the capacitor voltage, line terminal voltage, active power, and reactive power. To regulate these parameters, they are discovered and contrasted with reference values. The following are the membership duties of FLC to achieve this: error, change in error, and output. The following sources served as the basis for the FLC rules. The notation E stands for the system error, C for the change in error, and u for the control variable. A high error E value denotes the absence of a balanced state in the system. The controller should immediately increase the amount of its control variables if the system is out of balance in order to bring it back into balance. A low error E value, on the other hand, indicates that the system is nearly balanced.

Initial conditions and input data. The critical loads of 100 kW and 150 kVAr and noncritical loads of 100 kW and 100 kVAr are both taken into consideration into both cases capacitive and inductive. MATLAB/Simulink is used to model the hybrid power system with the ES as shown in Fig. 4. To lessen harmonics brought on by inverter switching transients, a harmonic filter is connected after the inverter [23]. To control voltage magnitude and frequency as well as to account for reactive power by load, an ES is connected prior to the load in parallel with the critical load and in series with the noncritical load [24, 25].

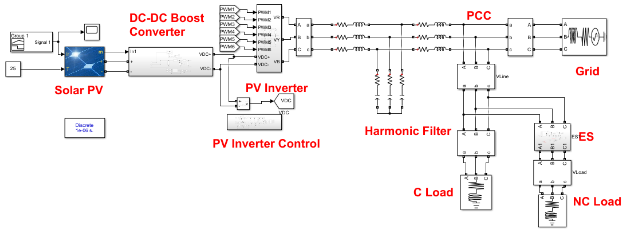

Fig. 4. Hybrid power system in MATLAB/Simulink

Simulation results. Case I: capacitive (voltage boosting) mode of operation of ES. To illustrate the voltage support capability of ES the disturbance source is programmed at $t = 0.2$ s to generate a voltage of 208 V. In order to restore the line voltage back to its nominal reference value the ES is activated at $t = 0.3$ s and voltage of the ES is increased from its near-zero value to about 175 V. As soon as ES is activated, it is observed that voltage across noncritical load decreases to 70 V as indicated in Fig. 5. The voltage is regulated back to its nominal reference value 230 V at t = 0.3 s. The corresponding instantaneous value of noncritical load voltage, ES voltage and critical load voltage are clearly indicates that current leads the voltage by 90°. Thus successful implementation of ES in capacitive mode is conducted using MATLAB.

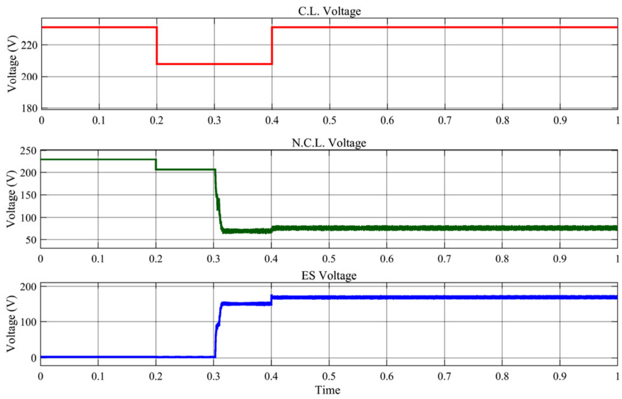

Fig. 5. Observed RMS value of critical voltage, noncritical voltage and ES voltage in capacitive mode

ES voltage in capacitive mode, critical load voltage, and noncritical load voltage are shown in Fig. 6.

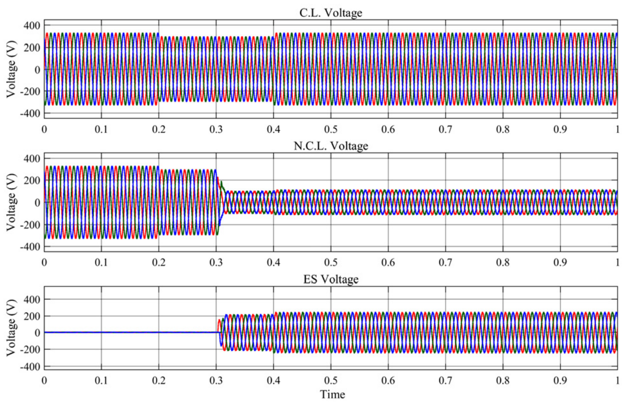

Fig. 6. Observed instantaneous value of critical, noncritical load voltage and ES voltage in capacitive mode

Case II: Inductive (voltage suppression) mode of operation of ES. To test the voltage suppression capability of the ES a disturbance source is programmed at $t = 0.2$ s to generate a voltage of 254 V.

In order to suppress the increased line voltage back to its nominal reference value the ES is activated at $t = 0.3$ s and voltage of ES is changed to stabilize the line voltage as shown in Fig. 7. As soon as ES is activated; it is observed that voltage across noncritical load increases to 250 V. Finally, the voltage is regulated back to its nominal reference value 230 V at $t = 0.3$ s. The corresponding instantaneous value of noncritical load voltage, ES voltage and critical load voltage clearly indicates that current lags the voltage by 90°, representing efficacious working of the ES in inductive mode. Thus successful implementation of ES in inductive mode is conducted using MATLAB.

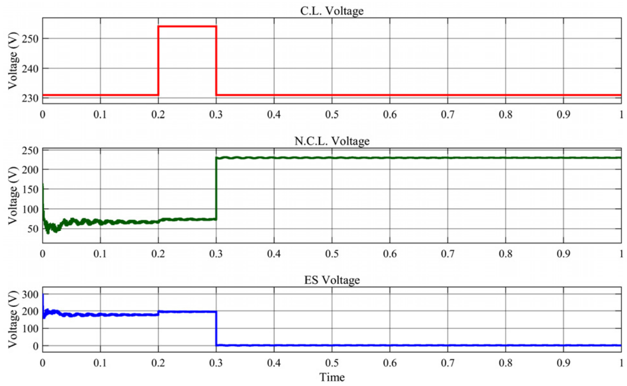

Fig. 7. Observed RMS value of critical voltage, noncritical voltage and ES voltage in inductive mode

The voltage of an ES operating in inductive mode is shown in Fig. 8 together with its critical load and noncritical load.

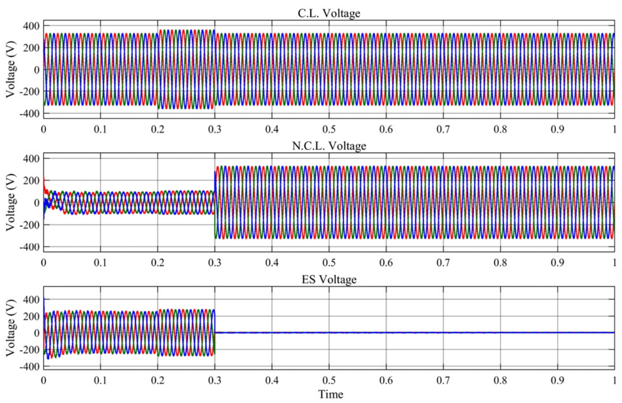

Fig. 8. Observed instantaneous value of critical, noncritical load voltage and ES voltage in inductive mode

Table 2 gives comparative results values in percentage with considering different load conditions and without ES and with ES.

Table 2

With and without ES simulation results

Parameter	Without ES 100 kW, 150 kVAr (CL) and 100 kW, 100 kVAr (NCL)	With ES 10 kW, 15 kVAr (CL) and 10 kW, 10kVAr(NCL)	With ES 100 kW, 150 kVAr (CL) and 100 kW, 100 kVAr (NCL)
Voltage variation, %	50	2	2.1
Frequency variation, %	5	0.1	0.2

Conclusions. It has been shown in this paper and previous research that electric spring is an effective approach for dealing with the issue of power system instability associated to alternate sources driven grids. The employment of a fuzzy control technique by an electric spring to maintain line voltage, power the important load, and increase the device's power factor is shown in this paper. The proposed fuzzy control approach is frequently contrasted with the conventional controller. It has also been demonstrated that voltage regulation and power system enhancement can be handled by a different organization. It is possible to verify the proposed converter by simulating it in the hybrid system using MATLAB/Simulink. The results from the electric spring under various lodes circumstances effectively stabilise the voltage.

Conflict of interest. The authors declare that they have no conflicts of interest.

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