International Journal of Industrial Electronics, Control and Optimization IECO
Vol. 5, No. 1, pp. 89-98, Jan (2022)

An Improved Fuzzy Controlled Back-to-Back Electric Spring Using Hybrid Structure of ES-1 and Shunt-APF to Improve Power Quality in Microgrids

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ABSTRACT

Electric spring (ES) is a new technology that can be used for fast demand-side management to balance the power between generation and consumption in smart grids. In this paper, the back-to-back structure of electric spring is controlled to operate simultaneously as electric spring and shunt active power filter (shunt-APF). That means, the series part of the back-to-back electric spring regulates the critical load voltage and applies the demand-side management and the parallel part operates as a shunt active power filter capable of power factor correction and current harmonic compensation. In the proposed structure, due to harmonic compensation and power factor improvement by the parallel inverter, the output power capacity of the electric spring is increased compared with the first and second generation of electric springs (ES-1 and ES-2), and the performance is improved in critical conditions. Additionally, to improve the robustness of the control system against uncertainties in the grid system, two fuzzy logic controllers are designed to control the voltage of the electric spring and the DC link voltage. The theoretical analysis is validated by simulation results using MATLAB/SIMULINK software.

Article Info

Keywords:
Active power filter, Back-to-Back converter, Electric spring, Fuzzy controller, Microgrid.

Article History:
Received 2021-10-18
Accepted 2021-02-21

I. INTRODUCTION

Nowadays, economic and environmental benefits cause increasing attention to renewable energy resources such as solar and wind energy. Because of intermittent feature of these resources, the generated power will be uncertain and unpredictable. Additionally, widespread application of these resources, causes uncertainty in power quality and instability of the power system [1-3]. So far, various approaches such as reactive power compensation equipment [4], energy storage devices [5], direct load control such as load shaving, on/off non-critical loads have been proposed to improve voltage fluctuation. Some of traditional approaches are not compatible with the future power networks [6-8]. Electric spring (ES) is a new integrated technology that combines with non-critical loads to make smart loads. This technology is capable of voltage regulation through power consumption control of non-critical loads. In a smart load, an electric spring is connected in series with a non-critical load. Using electric spring, the power fluctuations in the grid are applied to the non-critical

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load which does not require high power quality, and in this way the critical load voltage is stabilized. Smart load is an adaptive structure that can automatically maintain the power balance between the supply-side and the demand-side. In [9-11], it was shown that the demand side response (DSR) is achievable in non-critical resistive loads. Using DSR, the grid voltage regulation and active power management is done by managing electrical loads.

So far, four versions of ES have been suggested. The first version (ES-1), which has a capacitor on its DC link, can only inject/absorb reactive power [12]. While, the second version (ES-2) can manage both the active and reactive power as the capacitor in the DC link is replaced with a voltage source such as a battery pack [13]. The third version (ES-3) is a new type of ES without non-critical load (NCL) [14]. As mentioned, the ES-2 has a wider operating range than the ES-1, which shows the importance of the active power exchange capability in the DC link. In [15] a new generation of electric springs was introduced that uses two converters in the form of back-to-back converters with a capacitor in the DC link (Fig. 1).

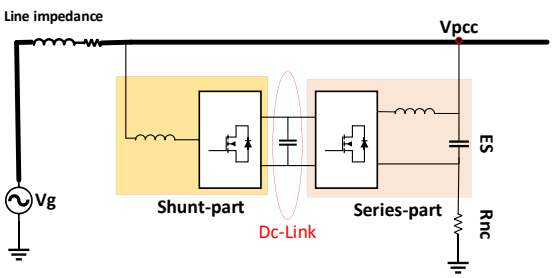


Fig. 1. Circuit structure of a back-to-back electric spring

The main function of the back-to-back electric spring is to maintain a stable voltage for a critical load. In [16] the back-to-back electric spring is introduced for main voltage stabilization and reactive power control. Due to uncertainties in the grid system such as load changes, the PI controller cannot operate properly [17]. In this condition, a fuzzy controller can be used to solve the problem. The detail of the fuzzy controller design method is discussed in [17, 18].

On the other hand, widespread application of renewable energy sources such as photovoltaic and wind energy which are connected to the grid through power electronic converters, along with an increasing application of power electronic devices to improve the efficiency and productivity in different industries, are new challenges for the grid power quality. Therefore, power quality improvement using active power filters attracts more attention. A shunt active power filter has the capability of harmonic compensation as well as reactive power compensation leading to power quality improvement.

In this paper, by using the back-to-back converters a new hybrid structure is proposed combining the first generation of electric springs (ES-1) and shunt active power filter to improve the power quality in microgrids. In this structure, the active power exchange capability is added to the ES-1 and the current harmonics and reactive power of the nonlinear load are compensated. Using an improved fuzzy controller, the robustness of the system is enhanced and the critical load voltage is adaptively stabilized.

II. HYBRID STRUCTURE OF ES-1 AND SHUNT ACTIVE POWER FILTER

In the proposed structure, the series part is a full-bridge inverter and is connected in series with the non-critical load, which forms a smart load (Fig. 2). The control system of the series part, adjusts the non-critical load voltage through comparison of the PCC voltage with its reference value. In this way, the power consumption of the non-critical load is adjusted adaptively, and as a consequence, the voltage of the critical load is regulated to its reference value using fast load demand response. In other words, to stabilize the critical load voltage at reference value, the power balance between the supply and demand side can be quickly controlled by adjusting the non-critical load voltage.

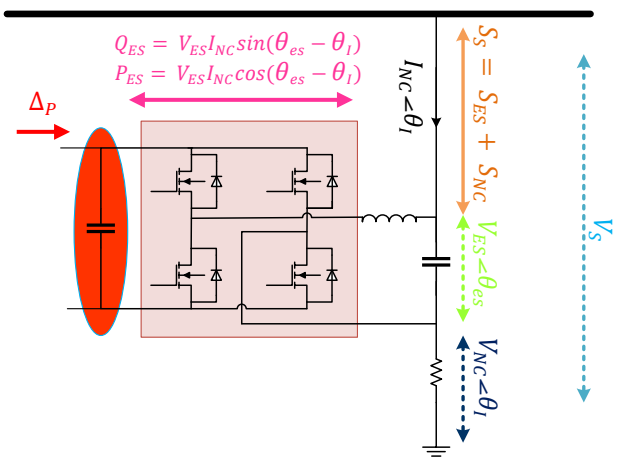


Fig. 2. Series part of the proposed structure

The shunt part of the proposed structure is a full-bridge inverter that connects to the grid through a passive filter (Fig. 3). The most important function of this inverter is to stabilize the DC link voltage. Indeed, this converter provides the possibility of active power exchange through the DC link. In addition, other capabilities such as current harmonics and reactive power compensation can also be provided by separating the active and reactive power from each other.

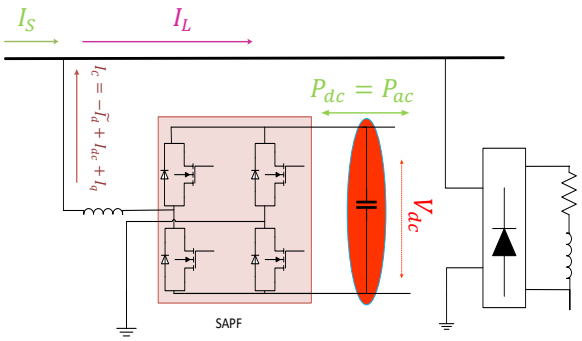


Fig. 3. Shunt part of the proposed structure

The ES-1 is connected to a capacitor in the DC link and can only exchange the reactive power at its output. Therefore, the output voltage of the ES-1 must be controlled so that it is perpendicular with the non-critical load voltage. This reduces the operating range of the electric spring. The ES-2 is connected to a battery in the DC link and can exchange active power as well as reactive power in its output. To increase the power exchange capability, the battery storage capacity must be increased which increases the cost and maintenance issues. Furthermore, for better performance, the state of charge (SoC) of the battery must be controlled which increases the control complexity. In the back-to-back structure introduced in [15], the power factor improvement and current harmonic compensation were not considered in the control system design. In the proposed hybrid structure, besides the load demand response capability of the electric spring, the power factor improvement and current harmonic compensation capabilities are provided. Also, using a fuzzy controller for the electric spring, the control performance such as robustness, can greatly be improved and the voltage stability and power quality can be improved significantly in microgrid systems.

III. THE PRINCIPLE OF OPERATION

A. Series Part

The series part of the proposed structure can exchange the active power as well as the reactive power in its output. Therefore, the output voltage phase angle of the series inverter can be controlled at any desired value. Although a capacitor is used in the DC link, but the required active power is provided by the shunt part. In a full H-bridge converter, if the loss is neglected, the power in dc and ac sides would be equal as (1).

$$P_{dc} = P_{ac} \quad (1)$$

Therefore, due to the possibility of providing active power in the DC link, it can be expected that the output voltage of the series part (ES) can be modulated with the desired angle and magnitude irrespective of the output current. This property provides four main operating modes for the ES:

1) Capacitive mode ($-jQ_{es}$): The ES injects pure reactive power and performs reactive power compensation. Therefore, the equivalent load will be more capacitive (V_{ES} 90 lagging V_{NC}) as in Fig. 4(a). Consequently, the line current is decreased and the critical load voltage is increased.

2) Inductive mode ($+jQ_{es}$): The ES absorbs pure reactive power and performs reactive power increment. Therefore, the equivalent load will be more inductive (V_{ES} 90 leading V_{NC}) as in Fig. 4(b). Consequently, the line current is increased and the critical load voltage is decreased.

3) Positive resistive mode ($+P_{es}$): The ES voltage is positive and absorbs active power (V_{ES} in phase with the V_{NC}) as in Fig. 4(c). Consequently, the line current decreases due to the non-critical load voltage decrement. Thus, the critical load voltage is increased.

4) Negative resistive mode ($-P_{es}$): The ES voltage is negative and injects an active power (180° phase difference between V_{ES} and V_{NC}) as in Fig. 4(d). Consequently, the line current increases due to the non-critical load voltage increment. Thus, the critical load voltage is decreased.

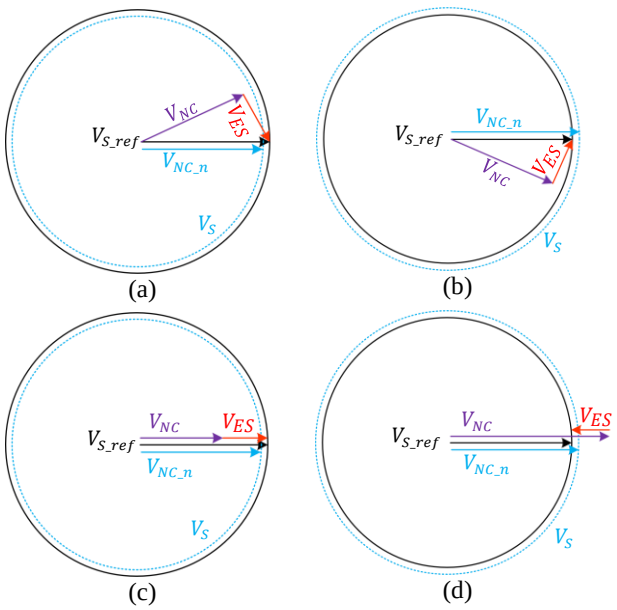


Fig. 4. Four main operational modes of the back-to-back ES

The other operational modes of the back-to-back electric spring are as follows:

5) Inductive-positive resistive mode ($P_{es} + jQ_{es}$) as in Fig. 4(e).

6) Inductive-negative resistive mode ($-P_{es} + jQ_{es}$) as in Fig. 4(f).

7) Capacitive-positive resistive mode ($P_{es} - jQ_{es}$) as in Fig. 4(g).

8) Capacitive-negative resistive mode ($-P_{es} - jQ_{es}$) as in Fig. 4(h).

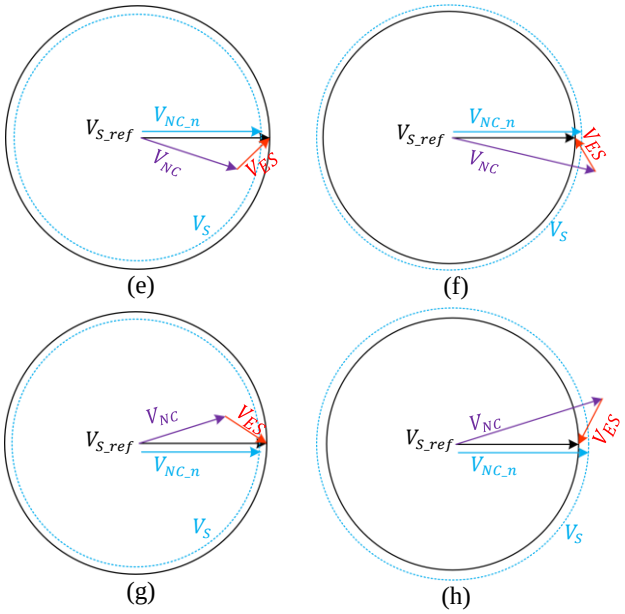


Fig. 5. Four other operational modes of the back-to-back ES

In all modes, the non-critical load is assumed to be a resistance load, and therefore its voltage (V_{NC}) and current (I_{Nc}) are in phase.

The relationship between the ES voltage (V_{ES}), line voltage (V_S), and non-critical load voltage (V_{NC}) is given by:

$$|V_s|\angle 0^\circ = |V_{ES}|\angle\theta_{es} + |V_{NC}|\angle\theta_{nc} \quad (2)$$

The non-critical load current I_{Nc} can be expressed as:

$$I_{Nc} = |I_{Nc}|\angle\theta_I \quad (3)$$

Where $|I_{Nc}|$ and θ_I are magnitude and phase angle of the non-critical load current, respectively.

The apparent power at the PCC in steady-state condition can be expressed as follows:

$$|S_S|\angle\delta_s = |S_{ES}|\angle\delta_{es} + |S_{NC}|\angle\delta_{nc} \quad (4)$$

Where, $|S_S|$, $|S_{ES}|$, and $|S_{NC}|$ are magnitudes of the apparent powers exchanged at the PCC, electric spring, and non-critical load, respectively. Also, $\angle\delta_s$, $\angle\delta_{es}$, and $\angle\delta_{nc}$ are phase angles of the above- mentioned apparent powers with respect to the voltage $V_S\angle 0^\circ$. The apparent powers can be expressed as follows:

$$\begin{cases} |S_S|\angle\delta_S = |V_S|\cdot|I_{Nc}|\angle -\theta_I \\ |S_{ES}|\angle\delta_{es} = |V_{ES}|\cdot|I_{Nc}|\angle(\theta_{es}-\theta_I) \\ |S_{NC}|\angle\delta_{nc} = |V_{NC}|\cdot|I_{Nc}|\angle(\theta_{nc}-\theta_I) \end{cases} \quad (5)$$

Generally, the apparent power can be written as:

$$S\angle\emptyset = |S|\text{Cos}(\emptyset) + j\cdot|S|\text{Sin}(\emptyset) = P + jQ \quad (6)$$

Assuming the load reactive power is controlled by the shunt active power filter. Therefore, the electric spring only control the exchanged active power which is expressed by (7).

$$P_S = P_{ES} + P_{NC} \quad (7)$$

Using (5) and (6), the active powers can be expressed as follows:

$$\begin{cases} P_{ES} = |I_{NC}|.|V_{ES}|.\text{Cos}(\theta_{es}-\theta_I) \\ P_{NC} = |I_{NC}|.|V_{NC}|.\text{Cos}(\theta_{nc}-\theta_I) \\ P_S = |I_{NC}|.|V_S|.\text{Cos}(-\theta_I) \end{cases} \quad (8)$$

Substituting (8) into (7), P_{NC} can be written as follows:

$$P_{NC} = |I_{NC}|.|V_S|.\text{Cos}(-\theta_I) - |I_{NC}|.|V_{ES}|.\text{Cos}(\theta_{es}-\theta_I) \quad (9)$$

In accordance to (9), the magnitude and phase angle of the ES voltage ($|V_{ES}|$ and θ_{es}) can be used to control the active power of the non-critical load. In the case of the PCC voltage higher than its reference value, the series part (ES) controls the active power of the non-critical load in such a way that the line current increases as a result of increasing the power consumption by the non-critical load. Therefore, the voltage drop across the line impedance is increased and the critical load voltage regulates. For this purpose, the electric spring works in negative resistance mode. That is, by generating a voltage in the opposite sign of the V_{NC}, the non-critical load voltage is increased and caused the increment of the non-critical load current. To generate the negative voltage, the electric spring must absorb the active power from the DC link.

In the case of the PCC voltage lower than its reference value, the series part (ES) controls the active power of the non-critical load in such a way that the line current decreases as a result of decreasing the power consumption by the non-critical load. Therefore, the voltage drop across the line impedance is decreased and consequently, the critical load voltage is regulated. For this purpose, the electric spring works in positive resistance mode. That is, by generating a voltage in phase with V_{NC}, the non-critical load voltage is decreased and caused the decrement of the non-critical load current. To generate the positive voltage, the electric spring must inject the active power into the DC link.

B. Shunt Part

Fig. 6 shows the hybrid structure of the electric spring and shunt active power filter. In this figure, the exchanged active and reactive power between the grid and the shunt active power filter are shown. The active power exchanged by the shunt active power filter (P_c) consists of two terms:

$$P_c = P_h - \Delta_P \quad (10)$$

Where, P_h is the active power exchange due to the current harmonic components which are injected by the shunt active

power filter. Also, the Δ_P can be written as:

$$\Delta_P = P_{loss} + P_{ES} \quad (11)$$

Where, P_{loss} is the switching loss and P_{ES} is the active power exchanged by the electric spring. Δ_P is used to generate the appropriate reference voltage. The exchanged power of the ES (P_{ES}) can be positive or negative.

In this paper, the instantaneous power theory or PQ theory is used to generate the reference current for the shunt active power filter. In the PQ theory, the single-phase voltage (V_C) and current (I_L) are converted into αβ frame using eq. (12).

$$\begin{bmatrix} X_\alpha \\ X_\beta \end{bmatrix} = \begin{bmatrix} X(\omega t) \\ X(\omega t - 90^\circ) \end{bmatrix} \quad (12)$$

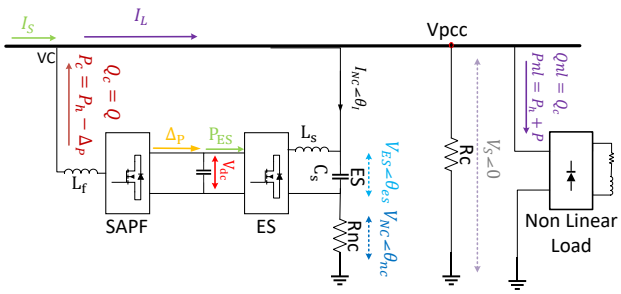


Fig. 6. Hybrid structure of the electric spring (ES-1) and shunt active power filter

IV. CONTROL DESIGN OF IMPROVED BACK-TO-BACK ELECTRIC SPRING

A. *Electric Spring*

The proposed hybrid structure regulates the PCC voltage using series part (ES-1) and compensates for the current harmonics and reactive power of the nonlinear load using the shunt part (shunt active power filter). A fuzzy controller is designed to control the series part which simulates the behavior of a PI controller to ensure the regulation of the PCC voltage to its reference value. Using the fuzzy controller, the robustness of the system will be improved and in case of uncertainty in the system parameters, the control system works properly.

At first, the PCC voltage is measured and compared with its reference value and the error signal (e) is obtained. The error signal and its changes are fed as inputs to the fuzzy controller. The fuzzy controller determines the modulation index 'm' as its output to reduce the error signal to zero. Then the modulation index 'm' is converted into a sinusoidal signal by the sinusoidal block, which is in phase or out of phase with the main voltage. Fig. 7 shows the control block diagram of the improved fuzzy controlled back-to-back electric spring.

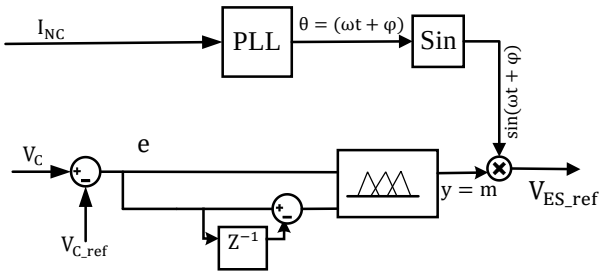


Fig. 7. Control block diagram of the improved fuzzy controlled back-to-back electric spring

Fuzzy logic is a data analysis method based on using non-precise values over a range to determine the correct correspondence to a particular group. It works by translating the experienced human's inference into fuzzy rules that determines what output should be produced for a particular range of input. The structure of a fuzzy controller is shown in Fig. 8.

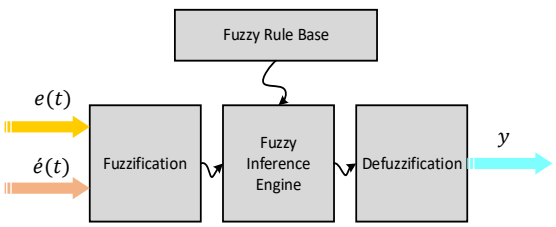


Fig. 8. Fuzzy controller

As shown in fig. 9, the values of the input error and change of error are normalized by an input scaling factor. To make the designed fuzzy controller universal, the ranges of the inputs $(e(t), \acute{e}(t))$ and the output (y) have been designed between [-1,1]. For this case, input variables comprise of error, $e(t)$, and change of error, $\acute{e}(t)$, are both defined by triangular membership functions with seven fuzzy subsets as {NL, NM, NS, Z, PS, PM, PL}, and the output y is represented as {NL, NM, NS, Z, PS, PM, PL}.

As shown in Table I, 49 fuzzy rules are defined to increase the fuzzy output accuracy. One of the fuzzy rules in this table is described for example. The last rule "if e=PL and é=PL, then y=PL" means that: if the difference between the measured and the reference voltages is a positive large value and the rate of change of this difference is also a positive large value, the electric spring output voltage will also be a large value. In this way, the behavior of a PI controller can be simulated using the fuzzy controller. The fuzzy inference system is Mamdani type and the defuzzification method is centroid.

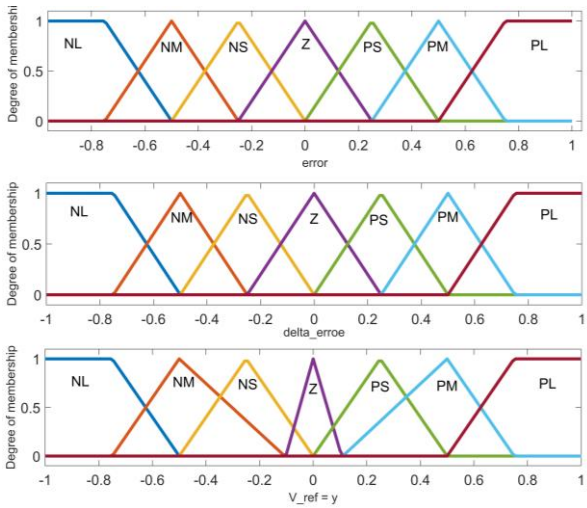


Fig. 9. Membership functions of the input and output

TABLE I
FUZZY RULES

e / é	NL	NM	NS	Z	PS	PM	PL
NL	NL	NL	NL	NL	NM	NS	Z
NM	NL	NM	NL	NM	NS	Z	PS
NS	NL	NL	NS	NS	Z	PS	PM
Z	NL	NM	NS	Z	PS	PM	PL
PS	NM	NS	Z	PS	PS	PL	PL
PM	NS	Z	PS	PM	PL	PM	PL
PL	Z	PS	PM	PL	PL	PL	PL

B. *Shunt Active Power Filter*

The current reference for the shunt active power filter is obtained from the PQ theory. The block diagram of this method is shown in Figure 10.

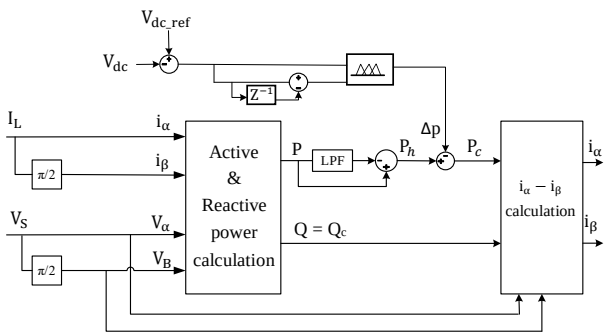


Fig. 10. Current reference extraction using pq method

The PQ theory determines instantaneous active and reactive powers based on α-β components as:

$$\begin{bmatrix} P \\ Q \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix} \begin{bmatrix} I_\alpha \\ I_\beta \end{bmatrix} = \begin{bmatrix} P_h \\ Q_h \end{bmatrix} + \begin{bmatrix} P_f \\ Q_f \end{bmatrix} \quad (13)$$

Where P_h is the harmonic active power component, P_f is the fundamental active power component, Q_h is the harmonic reactive power component and Q_f is the fundamental reactive power component. After calculating the active power, a low-pass filter is used to separate the harmonic active power component from the fundamental active power component. Also, the DC link voltage control loop is used to compensate for the switching power loss (Δ_P). To calculate the reference currents, the power loss must be considered. Finally, the reference currents in the αβ reference frame are calculated using the values of the active and reactive powers as given by (14).

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} V_\alpha & V_\beta \\ V_\beta & -V_\alpha \end{bmatrix}^{-1} \begin{bmatrix} P_h - \Delta_P \\ Q \end{bmatrix} \quad (14)$$

Also, a fuzzy controller is designed to control the DC link voltage which increases the robustness of the control system against parameter changes. Due to abbreviation, the similar explanations are omitted. The membership functions and fuzzy rules are given in Fig.11 and TABLE II, respectively.

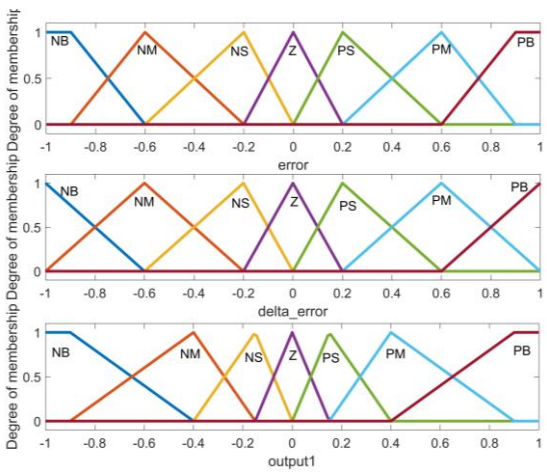


Fig. 11. Membership functions of the input and output

TABLE II
FUZZY RULES

e / é	NB	NM	NS	Z	PS	PM	PB
NB	NB	NB	NB	NB	NM	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

V. SIMULATION RESULTS AND DISCUSSIONS

In this section, the performance of the improved fuzzy controlled back-to-back electric spring is simulated using MATLAB/Simulink software. The simulation parameters are given in Table III.

A microgrid consisting of a critical load, a non-critical load and the proposed hybrid structure of electric spring (ES-1) and shunt active power filter is connected to a programmable power source through a transmission line.

The performance of the proposed system is evaluated under voltage suppression and voltage support conditions when a nonlinear local load is connected. The main voltage is set to 110 V and is increased or decreased in different time intervals.

A. Voltage Support Performance

In this experiment, the critical load voltage is assumed to be 105 V. Also, due to the nonlinear local load connection, the grid current is non-sinusoidal and contains harmonics and the power factor is not unity. The critical load voltage, ES voltage, and non-critical load voltage are shown in Fig. 12. Initially, the back-to-back electric spring is bypassed. The shunt active power filter is activated at t=0.2s to stabilize the DC link voltage and compensate the current harmonics. At t=0.6s, the series part (ES) is activated to regulate the PCC voltage to 110V. It can be seen that the voltage regulation function is performed well. The ES produces a voltage in phase with the PCC voltage to voltage support purpose and as a consequence, the non-critical load voltage decreases.

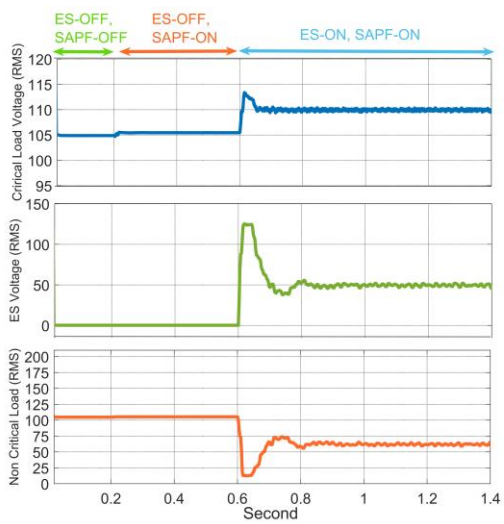


Fig. 12. Cririal load voltag (upper trace), electric spring voltage (middle trace) and non-critical load voltage (lower trace)

The simulation results of the shunt part (shunt active power filter) are shown in Figures 13 to 17. The shunt part activates at t=0.2s and compensates for the current harmonics and the reactive power of the nonlinear local load. Also, the series part is activated at t=0.6s. The compensation current generated by the shunt part is shown in Fig. 13.

The DC link voltage and the load power factor are shown in Figs. 14 and 15, respectively. Also, the source current THD is shown in Fig. 16. The THD value is reduced from 10% to less than 5% when the shunt active power filter is activated at t=0.2s and remains less than 5% after activating the series part (ES-1) at t=0.6s. Also, Fig. 15 shows that the PF improves after activating the shunt active power filter and the electric spring.

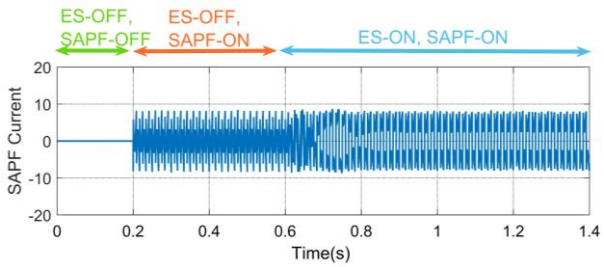


Fig. 13. The compensation current of the shunt active power filter

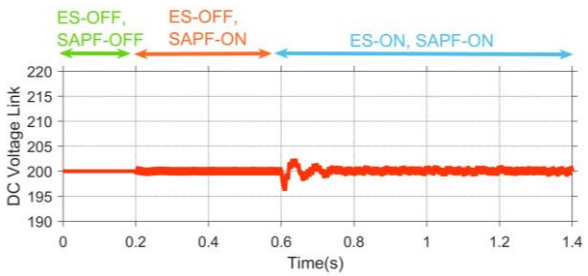


Fig. 14. The DC link voltage

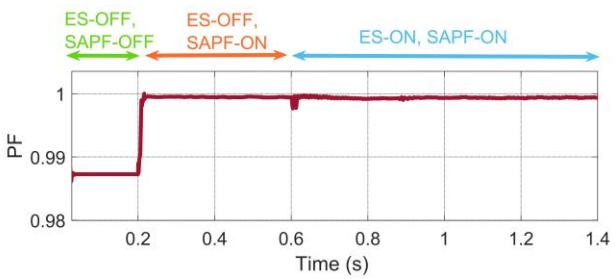


Fig. 15. The load power factor (PF)

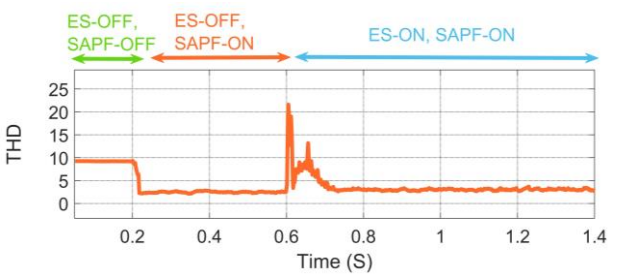


Fig. 16. THD of the source current

Fig. 14 shows that in the voltage support mode, after activation of the ES at t = 0.6s, it injects the active power into the DC link and the DC link voltage is increased. The shunt active power filter section absorbs the active power from the DC link and injects it back into the grid.

B. Voltage Suppression Performance

In the next experiment, the critical load voltage is assumed to be 115V. Also, due to the nonlinear load connection, the grid current contains harmonics and the power factor is not unity. The critical load voltage, ES voltage, and non-critical load voltage are shown in Fig. 17. Initially, the back-to-back electric spring is bypassed. The shunt part (shunt active power filter) is activated at t=0.2s to stabilize the DC link voltage and to compensate for the current harmonics. At t=0.6s, the series part (ES) is activated and regulates the PCC voltage to 110 V. The ES produces a voltage with 180° phase difference with the PCC voltage to voltage suppression purpose and as a consequence the non-critical load voltage increases.

The simulation results for the shunt part (shunt active power filter) are shown in Figs. 18 to 21. The shunt part activates at t=0.2s and compensates for the current harmonics and the reactive power of the nonlinear local load. Also, the series part is activated at t=0.6s. The compensation current generated by the shunt part is shown in Fig. 18.

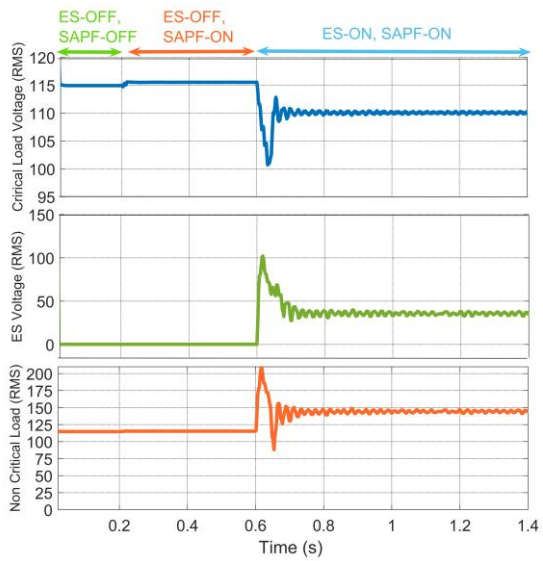


Fig. 17. Cririca load voltag (upper trace), electric spring voltage (middle trace) and non-critical load voltage (lower trace)

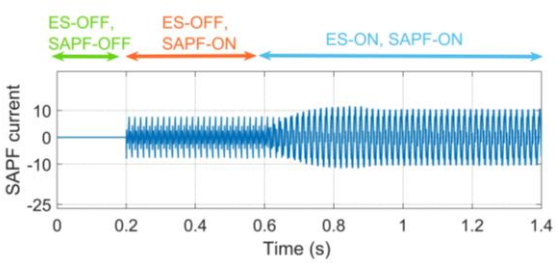


Fig. 18. Shunt active power filter compensation current

The DC link voltage and the load power factor are shown in Figs. 19 and 20, respectively. Also, the source current THD is shown in Fig. 21. The THD value is reduced from 10% to less than 5% when the shunt active power filter is activated at t=0.2s and remains less than 5% after activating the series part (ES-1) at t=0.6s. Also, Fig. 20 shows that the PF improves after activating the shunt active power filter and the electric spring.

Fig. 19 shows that in the voltage suppression mode, after activation of the ES at t = 0.6s, it absorbs the active power from the DC link and the DC link voltage is decreased. The shunt active power filter section absorbs the active power from the grid and injects it back into the DC link.

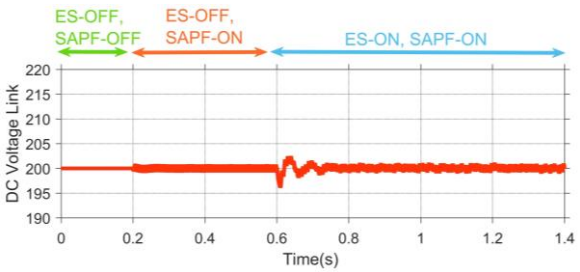


Fig. 19. The DC link voltage

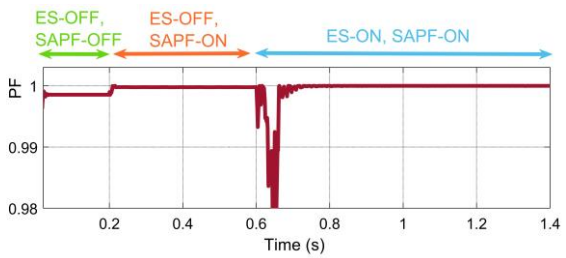


Fig. 20. The load power factor (PF)

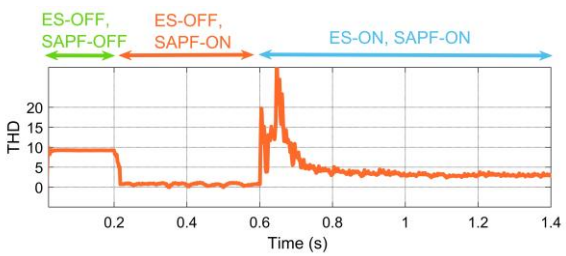


Fig. 21. The source current THD value

C. Robustness of the Fuzzy Conrol System of Electric Spring Against Parameter Variation

In this subsection, the performance of the fuzzy controller of the electric spring against the changes in the non-critical load parameter is shown.

In this experiment, the non-critical load resistance is changed as 20, 30, 40, and 50Ω. Simulation results for both PI and fuzzy controllers are shown in Fig. 22. In both methods, the electric spring is activated at t = 0.6S.

As shown in Fig. 22, when the non-critical load is equal to 50Ω, the PI controller is unable to adjust the PCC voltage. But, the fuzzy controller is capable of maintaining the PCC voltage in 110V regardless to the value of non-critical load. The resuts show that in the proposed structure, the fuzzy controller increases the robustness of the electric spring against parameter variations.

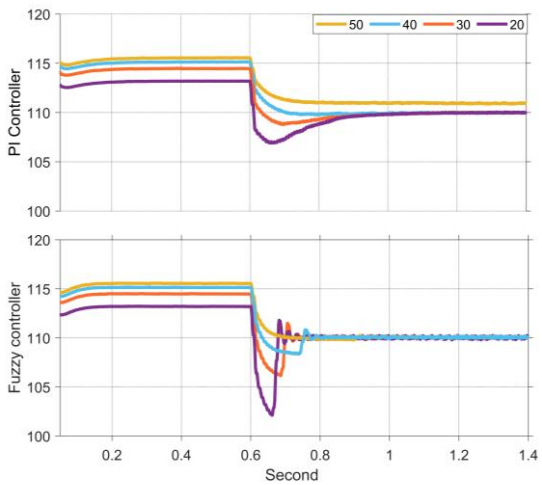


Fig. 22. The critical load voltage in case of parameter variation, PI controller (upper trace) and fuzzy controller (lower trace)

D. *Robustness of the Fuzzy Conrol System of the DC Link Voltage Against Parameter Variation*

In this experiment, the robustness of the DC link voltage control system is tested. The performance of the fuzzy controller against load parameter changes is compared with the PI controller.

For this purpose, the non-critical load resistance is changed to 30, 40 and 50Ω at t=0.6S. As shown in Fig. 23, both PI and Fuzzy controllers, control the DC link voltage and regulate it to 200V.

controller (upper trace) and fuzzy controller (lower trace)

However, by changing the non-critical load parameters, the performance of the PI controller is deteriorated in some cases and the overshoot and settling time are increased. But, using the fuzzy controller the control system performance is very good in all cases and the overshoot and settling time are acceptable.

The simulation results show that in case of using fuzzy controller, the robustness of the control system is increased and the DC link voltage is more stable than the case of using PI controller.

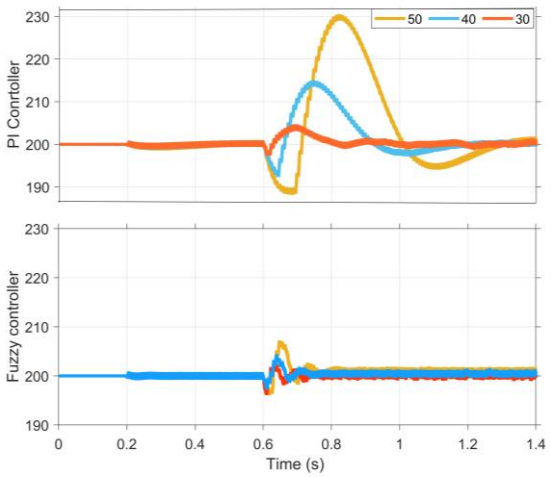


Fig. 23. The DC link voltage in case of parameter variation, PI controller (upper trace) and fuzzy controller (lower trace)

TABLE III
SIMULATION PARAMETERS

System and Loads	
Frequency	60HZ
Nominal System Voltage (V_S)	110V
Line Impedance	0.7Ω
	9mH
R/X Ratio of the System	0.02
Non-critical Load R_C	60Ω
Critical Load	50Ω
Voltage Limitation of Non-Critical Loads	35%
Nonlinear Load (Diode bridge with RL load)	13.34Ω
	50mH
Rating of the inverters	2 kVA
Electric Spring Specifications	
Inverter Type	Single Phase Full Bridge Inverter
Switching Frequency	8KHZ
Low-pass Filter Inductance L_S	3.1mH
Low-pass Filter Capacitor C_S	21µF
Shunt Active Power Filter Specifications	
Inverter Type	Single Phase Full Bridge Inverter
Switching Frequency	8KHZ
Regulated DC Bus Voltage	200V
DC Bus Capacitance	4500µF
Low-pass Filter Inductance L_f	8.3mH

VI. CONCLUSION

In this paper, an improved structure of a back-to-back electric spring is used capable of demand-side management and stabilizing the critical load voltage. This structure also

works as a shunt active power filter and compensates for the current harmonics caused by the nonlinear load and improves the power factor. Two robust fuzzy controllers are designed to control the voltage of the electric spring and the DC link voltage which have good performances in case of grid uncertainties such as load or line impedance changes. Using simulation results, the robustness of the improved fuzzy controlled back-to-back electric spring is shown against parameter variation.

REFERENCES

[1] I. Koutsopoulos, and L. Tassiulas, "Challenges in demand load control for the smart grid," *IEEE Network,* vol. 25, no. 5, pp. 16-21, 2011.

[2] X. Liang, "Emerging Power Quality Challenges Due to Integration of Renewable Energy Sources," *IEEE Transactions on Industry Applications,* vol. 53, no. 2, pp. 855-866, 2017.

[3] S. A. Shirmardi, M. Joorabian, and H. Barati, "Green Micro-Grid Operation Constrained to Reliability and Flexibility Indices in the Presence of Distributed Generations and Energy Storage Systems," *International Journal of Industrial Electronics Control and Optimization,* vol. 4, no. 4, pp. 397-407, 2021.

[4] L. Wang, C. Lam, and M. Wong, "Hybrid Structure of Static Var Compensator and Hybrid Active Power Filter (SVC//HAPF) for Medium-Voltage Heavy Loads Compensation," *IEEE Transactions on Industrial Electronics,* vol. 65, no. 6, pp. 4432-4442, 2018.

[5] C. Ju, P. Wang, L. Goel, and Y. Xu, "A Two-Layer Energy Management System for Microgrids With Hybrid Energy Storage Considering Degradation Costs," *IEEE Transactions on Smart Grid,* vol. 9, no. 6, pp. 6047-6057, 2018.

[6] Z. Bao, W. Qiu, L. Wu, F. Zhai, W. Xu, B. Li, and Z. Li, "Optimal Multi-Timescale Demand Side Scheduling Considering Dynamic Scenarios of Electricity Demand," *IEEE Transactions on Smart Grid,* vol. 10, no. 3, pp. 2428-2439, 2019.

[7] X. Kong, C. Li, F. Zheng, and C. Wang, "Improved Deep Belief Network for Short-Term Load Forecasting Considering Demand-Side Management," *IEEE Transactions on Power Systems,* vol. 35, no. 2, pp. 1531-1538, 2020.

[8] M. A. A. Pedrasa, T. D. Spooner, and I. F. MacGill, "Scheduling of Demand Side Resources Using Binary Particle Swarm Optimization," *IEEE Transactions on Power Systems,* vol. 24, no. 3, pp. 1173-1181, 2009.

[9] G. Buja, S. Giacomuzzi, Q. Wang, and M. Bertoluzzo, "Demand-Side Power Paradigm-Oriented Analysis of Reactive Electric Spring Stabilization Capabilities," *IEEE Access,* vol. 8, pp. 213662-213670, 2020.

[10] Y. Qi, T. Yang, J. Fang, Y. Tang, K. R. R. Potti, and K. Rajashekara, "Grid Inertia Support Enabled by Smart Loads," *IEEE Transactions on Power Electronics,* vol. 36, no. 1, pp. 947-957, 2021.

[11] J. Zhang, G. Ma, X. Lyu, M. Li, J. Xu, and X. Wu, "Research on Scheduling Control Strategy of Large-Scale Air Conditioners Based on Electric Spring," *International Journal of Electrical Power & Energy Systems,* vol. 124, pp. 106398, 2021.

[12] S. Y. Hui, C. K. Lee, and F. F. Wu, "Electric Springs—A New Smart Grid Technology," *IEEE Transactions on Smart Grid,* vol. 3, no. 3, pp. 1552-1561, 2012.

[13] S. Tan, C. K. Lee, and S. Y. Hui, "General Steady-State Analysis and Control Principle of Electric Springs With Active and Reactive Power Compensations," *IEEE Transactions on Power Electronics,* vol. 28, no. 8, pp. 3958-3969, 2013.

[14] C. K. L. a. S. Y. R. Hui, "Input AC Voltage Control Bi-directiobal Power Converters " *U.S.patent,* 2013.

[15] S. Yan, C. Lee, T. Yang, K. Mok, S. Tan, B. Chaudhuri, and S. Y. R. Hui, "Extending the Operating Range of Electric Spring Using Back-To-Back Converter: Hardware Implementation and Control," *IEEE Transactions on Power Electronics,* vol. 32, no. 7, pp. 5171-5179, 2017.

[16] Z. Rui, F. Shi, D. Shu, Z. Yan, and X. Luo, "A Flexible Multi-objective Coordinated Control Strategy for Smart Loads Based on Electric Springs." *IEEE/IAS Industrial and Commercial Power System Asia (I&CPS Asia),* pp. 1344-1349, 2020.

[17] M. S. Javaid, U. B. Irshad, A. Hussein, and M. A. Abido, "A Novel Fuzzy Logic Controller for Smart Load Voltage Regulation." *International Conference on Clean Electrical Power (ICCEP),* pp. 620-624, 2017.

[18] S. Disha, "Designing and Modeling Fuzzy Control Systems," *International Journal of Computer Applications,* vol. 16, 02/28, 2011.



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