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Electric Spring based Voltage Control of DC Microgrids using Intelligent Controllers

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Abstract: The Electric Spring (ES) is a piece of power electronic equipment used to boost system stability, lessen three-phase power imbalance, and increase power quality. When ES modifies the conventional methods of operation where the generated energy differs from the load energy, the new operational strategy where the load energy changes with the generation energy changes will be realized. Future sustainable microgrids (MGs) require essential components like solar and wind-generated electricity. The power imbalance between the generating side and the load side will be caused by RESs' intermittency, instability, and lack of prediction accuracy, among other traits. Additionally, both the grid's security and the caliber of the power being delivered will be impacted. This paper presents an effective idea known as the Electrical Spring for controlling mains voltage despite variations brought on by intermittent renewable energy sources in the DC microgrid setting. In this study, a DC-DC converter is equipped with a Fuzzy Logic Controller (FLC) to be able to examine power quality problems like, voltage ripple and voltage regulation. The MATLAB is used to run the simulation in the Simulink environment. The results of the artificial neural network (ANN)-based intelligent controller, Model Predictive Controller (MPC) and the conventional PI controller are compared with the performance parameters that the proposed FLC controller has obtained. A study based on Matlab simulation results is conducted and published to support the effectiveness and accuracy of the suggested control strategy.

Keywords: *Electric Spring (ES), PI control, DC-DC converter microgrids (MG), Artificial Neural Network (ANN), Fuzzy Logic Controller (FLC), Model Predictive Controller (MPC).*

I. INTRODUCTION

In large and micro grids, renewable energy sources like solar and wind energy are contrasted. Without considering the effects on voltage and frequency stability of the network, the addition of this non-conventional energy leads to disruption, blackouts, and grid vulnerability. Additionally, because non-conventional energy is sporadic and changeable by nature, if its installed capacity were comparable to that of conventional energy, it would be difficult to predict its generation, which would lead to voltage and frequency fluctuations during times of power system instability [1]. Demand-side management (DSM) techniques come in many forms, including load scheduling, energy stowage use, uninterrupted control of smart loads (SL), etc. This paper describes an innovative technique known as the "Electric Spring," that is more than the electrical circuit linked to the power supply in a certain way to control the potential at a specific point. The mechanical spring is referred to by the word spring. An ES could be utilized to dampen electrical oscillations as well as offer electrical support [2]-[4].

Hong Kong University developed the idea of ES to address the aforementioned issues. There are primarily two types of loads. Some loads, such heating or cooling equipment (boiling heater, air conditioning, etc.), are sensitive to voltage variations, whereas others are not. The renewable generating sources indicated above might not be reliable. Critical load (CL) will not function normally if the line voltage swings. To ensure that CL operates normally, the modification of ES transmits voltage variations (energy) to non-critical load (NCL). The imbalance brought on by the generation of renewable energy was resolved by the new operation strategy, which modulates the load energy in accordance with changes in the generation energy [5].

The cornerstone of the fight against global warming is the decarbonization of the power industry globally. This goal should be accomplished by drastically increasing the penetration of renewable energies in the electric system. This means that issues with grid stability, dependability, and power quality in systems that rely heavily on renewable energy sources need to be taken into account. Centralized control is employed in the current power network, where power generation is mostly based on load predictions. FACTS systems are utilized to regulate voltage and flow of power. The majority of the current power grids are typically built for high or medium voltage applications and are

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therefore unsuited for future low potential micro networks with considerable RES diffusions, such as rooftop solar PV and moderate power range wind turbines [6]-[9].

The ES expertise had been suggested for upcoming distributed MG to fulfil these criteria by transferring voltage variations to non-critical loads (NCLs), keeping the voltage changes across critical loads (CLs) well under the restrictions. While CLs can only withstand a small range of potential, NCLs can tolerate a vast range. The automated balancing of load demand and energy output by ES allows for the transfer. Combining ES & NCL creates the purported SL [10]. Voltage and frequency are controlled by regulating the reactive and active power flows, respectively, using the ES architecture. The active power flow from a PV module to a CL branch is controlled by an electric spring, which also provides voltage stability at the CL point. As a result, frequency variation is managed. These techniques enhance the quality of power. They are coupled in series with various types of NCL to build smart loads. Power characteristics of these intelligent loads will be modified adaptively to account for variations in the power system. According to the research, solar panels can be connected to the ES to balance supply and demand [11]-[16].

Shown are the fundamental perception and the first kind of ESs, which primarily function in reactive power reparation. The second form, which has eight compensating functions, is thoroughly explained in [17]. In the third iteration, converters connected to the grid in both directions but lacking NCL employ the active suspension concept. The expanding electric spring approach is presented for both AC and DC systems. A DC ES in the DC microgrid modifies the DC bus voltage and lowers harmonic and ripple content. In addition to filtering and lowering harmonics, it also incorporates battery storage, enabling continuous DC supply [18].

An electric spring based on a model predictive controller is suggested in this research. The DC power source for the critical and non-critical loads is a solar panel. The pulse generation method is an FLC method. Utilizing the Matlab/Simulink software, simulation is performed. The proposed methodology's implementation is verified by associating the different parameters with the other controllers. The outcomes attained demonstrate unequivocally that inclusion of ES decreases the network's dependence on the NCL. Using a simulation model created in Matlab/Simulink, the performance of the DCSES is examined. In order to reduce the DC micro-reliance grids on the main grid and ensure that the NCLs completely follow the profile of the IRES, FLC controller is used to produce pulses for the converter. With PI controller, MPC, ANN and FLC controller, voltage regulation, harmonics, and ripple are noticed. The next sessions compare and discuss the findings.

II. Configuration of the Proposed ES

The DCSES's fundamental design is shown in Figure 1 while the circuit for the suggested control scheme is shown in Figure 2.

Typically, the NCL is used to connect the ES. Inductive and capacitive modes are the two main compensation mechanisms used by ES to modify the line voltage. As the potential V_l is beyond its preset voltage V_{l_ref}, V_{ES} lags behind i_0 by 90° in inductive mode for potential reduction, where i_0 & V_0 are the current & voltage of the NCL, correspondingly. The line potential is increased by the electric spring in capacitive mode as soon as the potential V_l drops below the predetermined value V_{l_ref}.

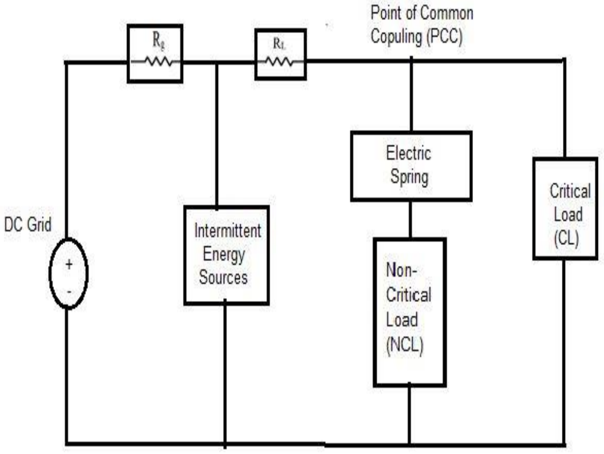


Figure 1 Block diagram of ES

A solar PV panel is regarded as an erratic source of DC power in the suggested circuit. It consists of a battery storage system, a CL, NCL, ES, and MPC controller (BSS). Depending on the generation, the MPC controller is set up as such NCL obtains rated potential otherwise below rated potential. To lessen the ripples in the DC, the inductor L_f functions as a filter. Utilizing the sporadic solar energy supply can also lessen the load on the battery unit.

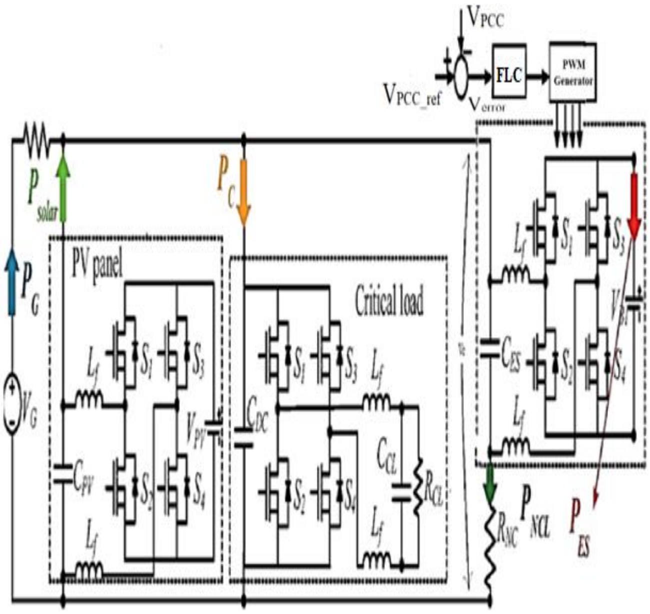


Figure 2 Control circuit of Proposed ES

III. Conception of ES

An ES in electrical form, is much like an Mechanical spring (MS). The force applied to an ideal MS comes from,

$$F = -kd \tag{1}$$

Where, k indicates the spring constant

d indicates the displacement.

The charge held in the electric spring according to equation (1),

$$q = \pm CV_c \tag{2}$$

Where, C indicates the capacitance value of the capacitor

V_c indicates the potential of the C.

The electric spring's potential energy is given by,

$$PE = \frac{1}{2}CV_c^2 \tag{3}$$

ES can restore the mains voltage V_S in a number of methods when it deviates from its reference value V_{S_ref}. Electric Spring creates a supportive voltage in potential boosting mode to raise the grid potential, while in voltage bucking (suppression) mode, it creates a suppressing voltage to reduce the main potential.

The ES's streamlined power circuit is shown in Figure 3 together with a voltage supply and transmitting cables. The results of applying KVL and KCL are as follows.

$$L_1 \frac{di_1}{dt} = V_{in} - V_l - (R_1 * i_1) \tag{4}$$

$$L_2 \frac{di_4}{dt} = V_a - V_{ES} - (R_2 * i_4) \tag{5}$$

By resolving the aforementioned equations, one can obtain the state-space representation of an ES.

$$\dot{x} = A_i x + B_i V_s + B_j u \tag{6}$$

$$y = C_i x + D_i V_s + D_j u \tag{7}$$

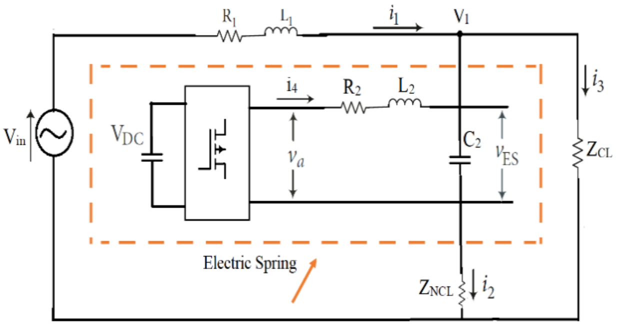


Figure 3 Equivalent Circuit of ES

Following matrices are used to calculate the coefficients of the equations above.

$$A_i = \begin{bmatrix} -\frac{Z_{NCL}Z_{CL} + R_1(Z_{NCL} + Z_{CL})}{L_1(Z_{NCL} + Z_{CL})} & 0 & \frac{Z_{CL}}{L_1(Z_{NCL} + Z_{CL})} \\ 0 & -\frac{R_2}{L_2} & -\frac{1}{L_2} \\ \frac{Z_{NCL}}{C_2(Z_{NCL} + Z_{CL})} & \frac{1}{C_2} & \frac{1}{C_2(Z_{NCL} + Z_{CL})} \end{bmatrix} \tag{8}$$

$$B_i = \begin{bmatrix} \frac{1}{L_1} \\ 0 \\ 0 \end{bmatrix} \tag{9}$$

$$B_j = \begin{bmatrix} 0 \\ \frac{V_{DC}}{2L_2} \\ 0 \end{bmatrix} \tag{10}$$

$$C_i = \begin{bmatrix} \frac{Z_{NCL}Z_{CL}}{Z_{NCL} + Z_{CL}} & 0 & \frac{Z_{CL}}{Z_{NCL} + Z_{CL}} \end{bmatrix} \tag{11}$$

$$D_i = 0 \tag{12}$$

$$D_j = 0 \tag{13}$$

Here,

V_{in} - supply potential
Z_{CL} - CL
Z_{NCL} - NCL
V_l - Potential at PCC(same as voltage across CL)
i_1 - line current
i_2 - current passing in the NCL
i_3 - current passing in CL
i_4 - current passing in ES

The voltage Vl should be kept constant and close to the pre-set value throughout. The state vector is expressed as x = [i1 i4 VES] T. In light of the foregoing state-space paradigm, determining the system output (Vl) should be our primary goal. Additionally, supply voltage Vin is regarded as an external disturbance.

IV. Control Methodologies for ES

The control schematic engaged in our research is presented in picture number 4. In this work a FLC controller is utilized for production of converter pulses.

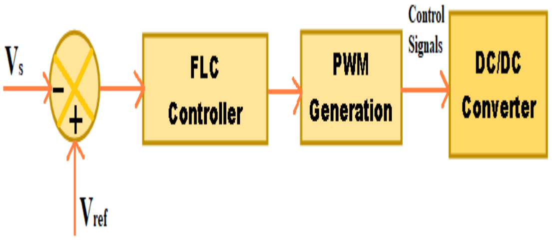


Figure 4 Basic Control diagram for ES based DC-DC Converter

(A) MPC Controller

A feedback control technique based on regularly solving optimal control problems is called model predictive control. Direct approaches for optimal control have become more popular due to their adaptability, especially in practical applications. A set of constraints are used by MPC, an advanced method of process control, to regulate a process. Since the 1980s, MPCs have been used in process control segments of oil refineries and chemical processes. Dynamic process models, which are typically linear empirical models produced as a result of system identification, are used by MPCs. The key advantage of MP controller is that it enables you to focus on future time slots while also optimizing the current time slot.

As opposed to a linear quadratic regulator, this is accomplished by optimizing a restricted time horizon while just applying the current time slot before optimizing repeatedly (LQR). MPCs can also predict upcoming occurrences and respond with the required control measures. PID controllers lack this ability to predict. Figure number 5 shows the main schematic of the MP controller.

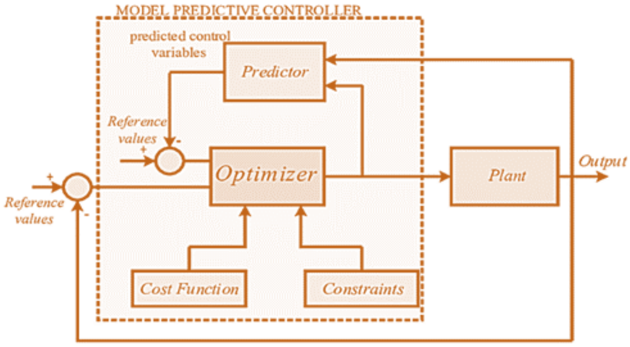


Figure 5 General Structure of MPC Controller

Emphasis should be placed on how closely the compensation approaches of ES are related to the phase angle of pre-set voltage V_{l_ref}. ES features include by utilising various angles of Vl ref, reactive and actual power compensation, O/p potential reduction, and power factor enhancement can be achieved.

(B) ANN Controller

Using the Levenberg Marquardt-based back propagation (LMBP) technique, the neural network is trained. The flowchart in figure 6 illustrates the neural network training method. Using normalized, previously processed data, the LMBP algorithm predicts and visualizes the correlation pattern between input and output. This algorithm is more precise and converges more quickly. The 100 values used in this procedure were produced through a Matlab simulation in which the training set consisted of 70% of the data records, the testing set of 15%, and the validation set of 15%. The ANN was constructed using an I/p layer, two hidden layers, and an O/p layer. Ten neurons are present in each buried layer. The output layer employs the purelin linear transfer function.

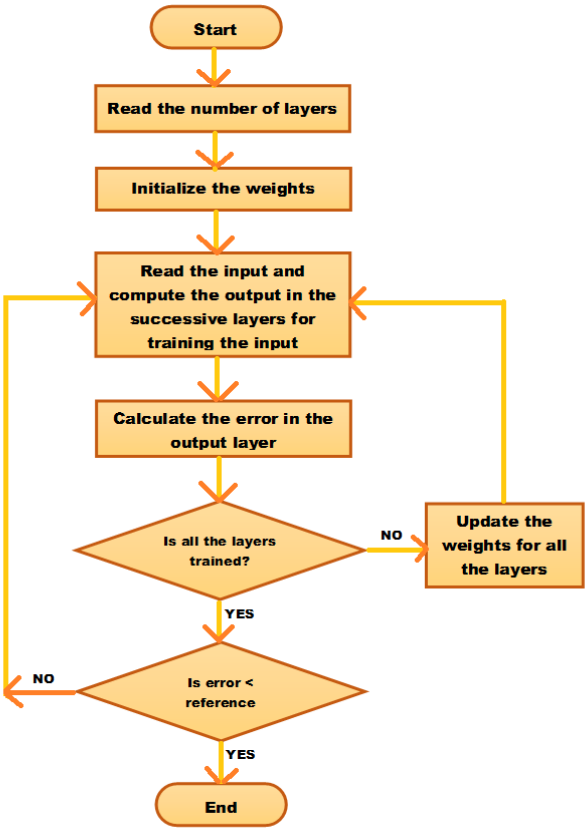


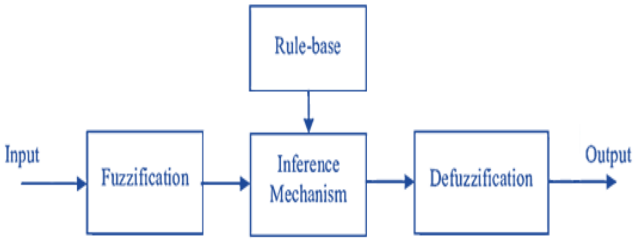
Figure 6 ANN Network 's Flowchart

(C) FLC Controller

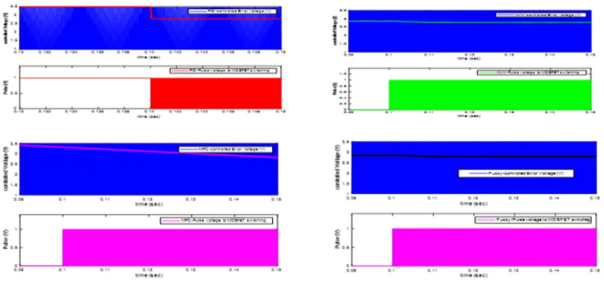
By creating a rule basis that controls the system's behavior, the fuzzy logic controller (FLC) is a technique for automating language control techniques. One of the most well-thought-out approaches to distributed power optimization problems is FLC. FLC functions have undergone extensive research to increase their capacity for dealing with difficulties with expert systems. Creating a fuzzy logic controller for incorporation into the Fuzzy Logic toolbox from MATLAB/Simulink served as the foundation for microgrid.

With the help of fuzzy, you can easily draw exact conclusions from muddled or inaccurate data. Compared to typical controllers, FLC has a number of benefits, including control simplicity, affordability, and the flexibility to be built without knowing the entire mathematical model of the process. The components of an FLC include fuzzification, defuzzification, rule base, input, and output. As shown in Figure 7, the controller is often placed between the input and output.

Figure 7 General structure of FLC



We took into account three linguistic variables (Negative, Positive, and Right) for the input "Error," and three linguistic variables (Up, Down, and No Change) for the output "Control." For the purpose of charging and discharging the battery, the fuzzy controller generated the proper switching pattern. The fuzzy logic controller was given four inputs to compare the DC bus voltage and a reference voltage.



V. Results and Discussions

The effectiveness of the recommended control mechanism is examined by MATLAB/SIMULINK simulation simulations, and the findings are presented in the figures 8 through 20. A list of several simulation-related parameters can be found in [7].

Figure 8 Pulse Generated for the DC-DC converter switch using the a) PI Controller b) ANN Controller c) MPC Controller d) FLC Controller

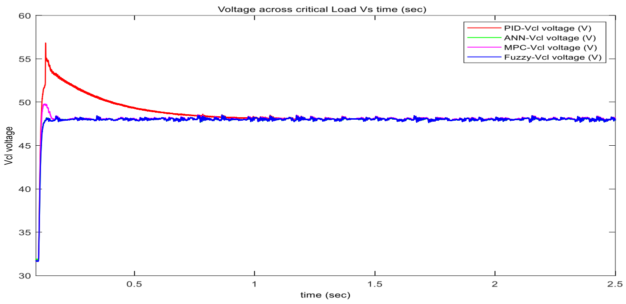


Figure 9 Voltage across CL for all types of Controllers

Voltage, current, and power output across critical and non-critical loads employing various controllers are depicted in Figures 9 to 14. Figures 9 to 11 shows the graphs of the CL and that of 12 to 14 depicts the graphs of the NCL. The voltage of the ES for the different controllers is displayed in the figure number 15. Similarly, the figure numbers 16 and 17 shows the current and power in the inserted electric spring of the proposed control methods.

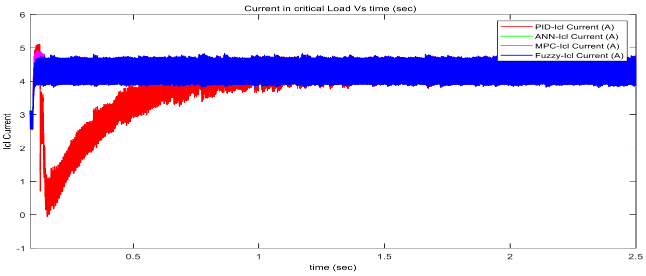


Figure 10 Current through CL for all types of Controllers

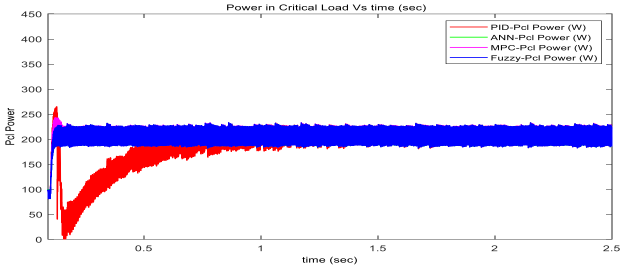


Figure 11 Power in CL for all types of Controllers

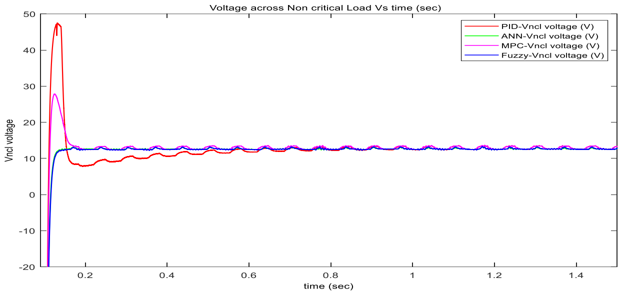


Figure 12 Voltage across NCL for all types of Controllers

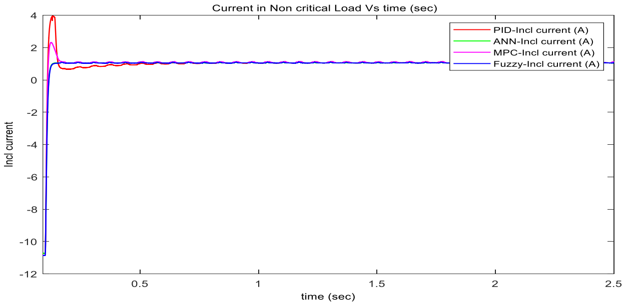


Figure 13 Current in NCL for all types of Controllers

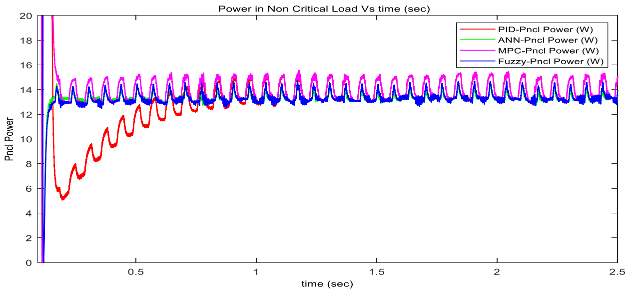


Figure 14 Power in NCL for all types of Controllers

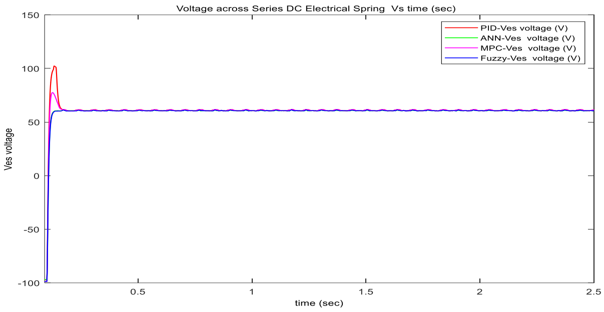


Figure 15 Voltage across ES for all types of Controllers

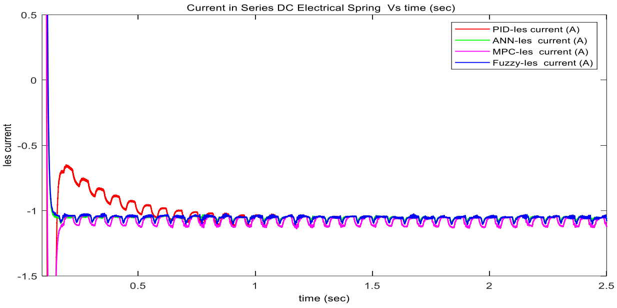


Figure 16 Current through ES for all types of Controllers

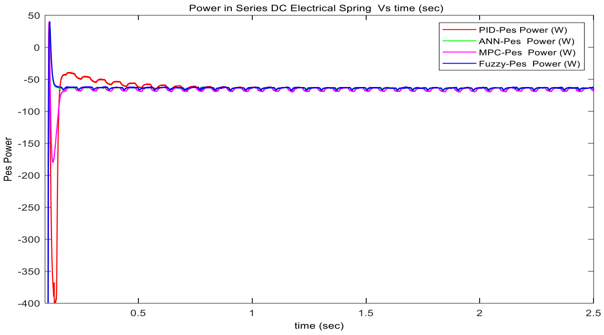


Figure 17 Power in ES for all types of Controllers

The regulated quantities due the introduction of the ES and various controllers are displayed in the figures 18 to 19. The current and potential in the DC bus of the suggested control methods are similarly shown in figures 18 and 19 respectively. The DC-DC converters output voltage without and with filters are illustrated in the figure 20. It can be clearly observed that there is a considerable reduction in the ripple content of the voltage waveforms.

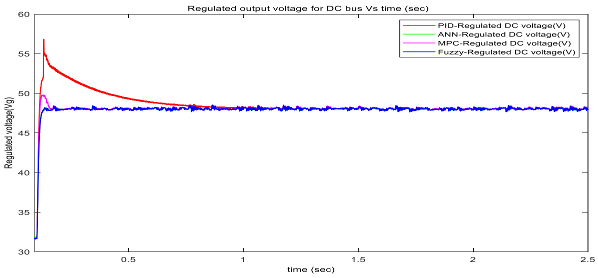


Figure 18 Regulated Output Voltage across DC Bus

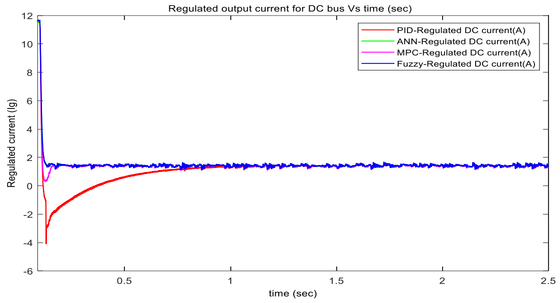


Figure 19 Regulated Output Current in DC Bus

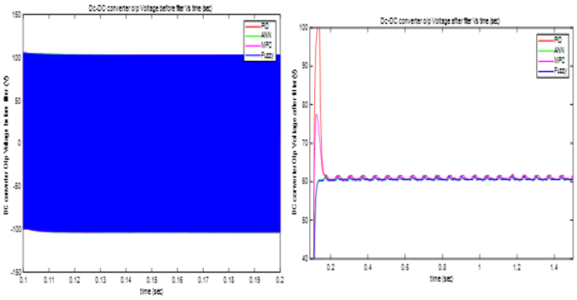


Figure 20 Converter Output Voltage without and with Filter

VI. Conclusion

Due to the intermittent nature of renewable energy sources and fluctuations in demand, distribution networks will experience significant voltage shifts that are intolerable for the bus supplying important loads. In a distribution system using ES, this research offers a successful voltage control technique for vital bus voltage support. Grid over-voltages are brought on by excessive power production, whereas grid under-voltages are brought on by insufficient power production. An innovative control approach is put forth in this study to address the aforementioned problem in the context of a DC microgrid. The proposed FLC controller in this work is demonstrated to be efficient in resolving the concerns listed, and the outcomes highlight the efficiency of the method. When compared to the ANN controller, MPC and traditional PI controller, the recommended FLC controller provides superior voltage management and reduced ripple. The simulation was done using MATLAB/Simulink, and the results show that the suggested controller is reliable. We may draw the conclusion that the suggested configuration of ES could manage the intermittent nature of RES within a DC micro-grid.

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