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Research Paper

Power Flow Controller with PI and Fuzzy Logic-Based Controllers During Fault Scenarios

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***Abstract*— The rapid evolution of modern power systems is fueled by increasing energy demands, the growing integration of renewable energy sources, and the rising complexity of load behaviors. These changes have made it more difficult to ensure reliable and stable system operation, especially during fault conditions. Traditional methods are often inadequate to address key challenges such as voltage regulation, transient stability, and power flow control. As a result, the performance of various advanced controllers has been studied to meet these emerging operational demands**

Keywords—UPFC ,FCTCR, Fuzzy logic controller

1.INTRODUCTION

Flexible AC Transmission Systems (FACTS) devices have demonstrated significant effectiveness in improving the controllability and stability of power transmission networks. Among these, the Integrated Power Flow Regulator stands out for its capability to simultaneously manage transmission voltage, impedance, and phase angle—offering a comprehensive solution for power flow regulation [2]. The Unified Power Flow Controller (UPFC), which combines series and shunt compensation within a single framework, is particularly effective under both steady-state and transient operating conditions.

2 Literature review

Previous research has thoroughly investigated the dynamic behaviour of Unified Power Flow Controllers (UPFCs), particularly emphasizing their ability to quickly respond through series voltage injection. This rapid response, coupled with the UPFC's capability to maintain voltage stability, enables smooth transitions between stable operating states. Such characteristics highlight the controller's adaptability and reliability under a wide range of system conditions.

UPFCs have proven effective in regulating power flow, especially within a Single Machine Infinite Bus (SMIB) system. In this context, the Hybrid Power Flow Controller (HPFC) has been studied as a complementary solution. The HPFC utilizes two half-rated voltage source converters configured in both series and parallel arrangements. These are supported by capacitive energy storage units that supply significant reactive power, thereby efficiently meeting the system's operational needs to further enhance control

Fuzzy Logic-Based Controllers (FLCs) have been integrated with traditional Proportional-Integral (PI) controllers to enhance control performance in power systems. Fuzzy logic offers a robust framework for managing the nonlinearities and uncertainties inherent in such systems. While FLCs can be implemented on general-purpose processors, deploying them on specialized embedded hardware significantly boosts computational efficiency and reduces costs. FLCs operate by processing input variables and selecting appropriate control actions based on a predefined set of linguistic rules.

Recent advancements have aimed at optimizing FLCs through the use of Genetic Algorithms (GAs). These evolutionary techniques improve the fuzzy system's rule base and membership functions, resulting in enhanced adaptability and performance. When combined with PI controllers, GA-optimized FLCs form intelligent, adaptive control systems capable of delivering superior regulation and stability in UPFC-equipped power networks.

Fuzzy Logic Control (FLC) is more effective than traditional PI controllers in handling system nonlinearities and uncertainties. It operates without the need for an accurate mathematical model, making it highly adaptable to complex power system conditions.

Artificial Neural Networks (ANNs) learn from data to model and control system behaviour, making them well-suited for adaptive and nonlinear control applications. However, they require a training phase and may face challenges in generalizing to unseen conditions.

Model Predictive Control (MPC) predicts the future behavior of the system and determines optimal control actions accordingly. It is capable of managing multiple control objectives and constraints simultaneously, making it a powerful tool for advanced power system regulation.

3. Methodology

3.1 PI-Based UPFC's Basic Structure

Figure 1 illustrates the basic structure of a PI-based Unified Power Flow Controller (UPFC) used for power flow management. In this configuration, the UPFC is installed between the sending and receiving ends of a transmission line. The system's performance is evaluated under the occurrence of a Line-to-Ground (LG) fault to assess the controller's effectiveness in managing power flow and maintaining system stability during fault conditions

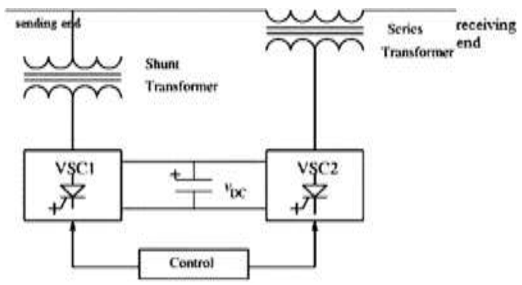

Figure 1 UPFC control

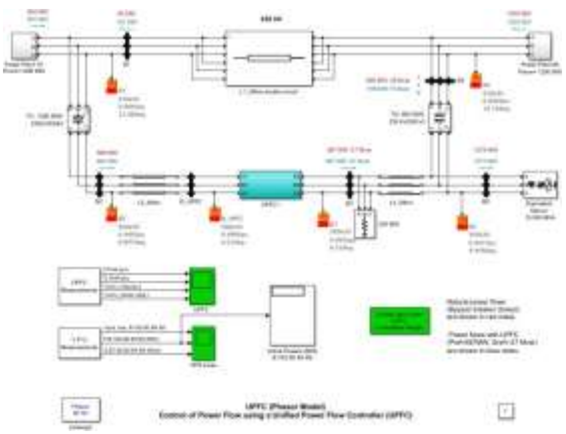

Figure 2: Detailed Architecture of UPFC

The DC voltage controller plays a vital role in maintaining the stability of the DC link by generating a corrective control signal through the comparison of the actual DC link voltage with a predefined reference value. In electrical and power electronic systems, the DC voltage controller is a critical component responsible for regulating the DC voltage to a desired level. These controllers are widely used in various applications, including DC-DC converters, renewable energy systems, electric vehicles, and High Voltage Direct Current (HVDC) transmission systems..

3.2 Analysis of Fuzzy Logic Systems

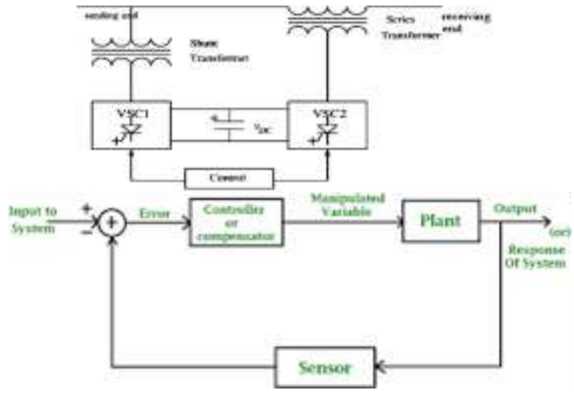

Figure-3: A basic fuzzy logic controller model

A basic fuzzy logic controller consists of the following key components, as illustrated in Figure 3:

Fuzzification: This is the process of converting crisp numerical inputs into fuzzy values. Inputs are mapped to fuzzy sets that represent linguistic variables such as "low," "medium," or "high."

Fuzzy Logic Rule Set: This is a collection of if-then rules that define the system's behavior based on the fuzzy input values. Example rules include:

if temperature is "increasing" and humidity is "inverse of temperature," then fan speed should be "fast."

If temperature is "low" and humidity is "high," then fan speed should be "slow."

3.3 AI Tools

Inspired by the structure of biological neurons, an Neural Network with artificial intellligience is made up of a network of interconnected nodes known as artificial neurons. Each link sends impulses to neighbouring neurons, much like a synapse in the human brain. After processing the input, an artificial neuron may send a signal to other neurons that are connected to it, depending on the outcome. Each connection's signal is represented by a real integer, and the biased sum of the neuron's inputs is exposed to a non- linear role to control the neuron's output. Together with the neurons, these connections also referred to as edges—are usually given weights that are modified through- out the learning process.

3.4 Training Set

In order to learn (or be trained), neural networks must process samples that have a known "input" and a matching "target result." The network creates probability- weighted correlations between the input and the outcome during this process, which include

The process starts with data preparation, where raw features are normalized (e.g., to [0,1] or zero mean/unit variance) to ensure faster convergence and balanced feature influence. The information is then divided into training, validation, and test sets for model learning, tuning, and final evaluation.

Next, the neural network architecture is defined, comprising an input layer (matching feature dimensions), hidden layers (for pattern learning), and an output layer.

Activa tion functions like ReLU (for hidden layers), sigmoid, or SoftMax (for output layers) present non-linearity, allowing the model to learn complex associations.

During training, forward propagation computes outputs layer-by-layer using current weights and biases. These outputs are compared to actual targets using a loss function— MSE for regression or Cross-Entropy for classification—to quantify prediction errors. Gradients, calculated via back propagation, indicate each weight's impact on prediction error in an artificial neural network (ANN). Optimization algorithms like SGD or Adam use these gradients to iteratively update weights and minimize the loss function. This process—comprising forward propagation, error calculation, back propagation, and weight updates—is repeated over multiple epochs.

4. Result

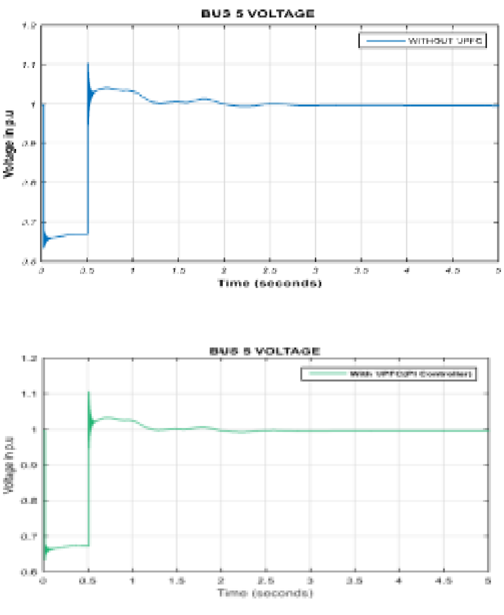

Figure 4: Bus 5's voltage (bus with LG fault)

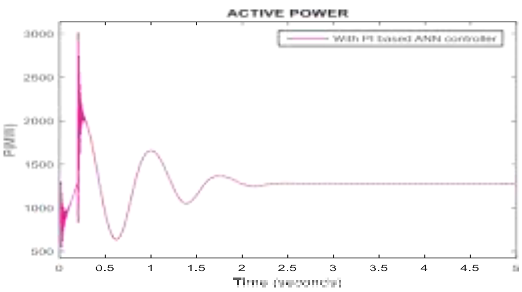

Figure 5: Supplying BUS 5 with active power (bus with LG fault)

Conclusion

The ability of the Unified Power Flow Controller (UPFC) to mitigate the effects of a line-to-ground (earthing) fault at Bus 5 has been thoroughly evaluated. The system's behavior was studied under various control strategies, including a conventional PI controller, a PI-based Fuzzy Logic Controller, and a PI-based Artificial Neural Network (ANN) controller. The analysis confirms that the UPFC effectively supports both active power and reactive power during fault conditions, thereby enhancing system stability and improving dynamic performance under disturbances

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