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Enhancing Power System Stability Using an Emotional-Based Intelligent Controller

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***Abstract*—This study explores the use of an emotional-based controller for transient stability and voltage regulation in a power system. The design of the controller draws inspiration from the emotional reactions observed in the human brain. The performance of the closed-loop controller is evaluated under both standard and faulty power system conditions. The robustness of the proposed controller is demonstrated through hardware-in-the-loop implementation and MATLAB/Simulink simulations. The findings confirm the superior performance of the controller under consideration.**

I. Introduction

Transient stability refers to the ability of a power system to maintain synchronous operation following a disturbance, such as a three-phase ground fault or a sudden change in the requested input voltage. This crucial aspect of power system stability is vital for ensuring the reliability and security of electrical grids. When a disturbance occurs, generators may temporarily lose synchronism with each other due to differences in mechanical torque or electrical phase angles [1]. Transient stability analysis involves studying the dynamic response of the system to such disturbances, evaluating factors such as rotor angle stability and the ability of generators to remain in synchronism. Mitigation strategies, such as the use of power system stabilizers or coordinated control schemes, are employed to enhance transient stability and prevent cascading failures that could lead to blackouts [1], [2], [3]. Due to the complex dynamics model of a power system, nonlinear control methods such as passivation control, point-wise min norm, HJB, and Melnikov have been employed for transient stability and voltage regulations [4], [5], [6], [7], [8]. To improve the overall performance of a power system, power converters have been used in power systems for power factor correction and harmonic elimination. Significant research has been completed to improve the power quality in a grid network [9], [10].

Inspired by the human brain's emotional learning process, a Brain Emotional Learning Based Intelligent Controller (BELBIC) incorporates principles of artificial intelligence and neural networks to mimic the adaptive and self-learning capabilities of biological systems. It functions as an intelligent controller capable of dynamically adjusting control actions based on real-time system conditions and the emotional state, which represents the system's response to change [11], [12].

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The method has been employed in several works so far. In [13], the BELBIC controller is used to enhance the tracking performance of a permanent magnet synchronous motor. The authors in [14], used the controller to regulate the level of the quadruple tank system.

In this paper, the emotional controller is used as an innovative approach applied in power systems to enhance system performance, particularly in addressing dynamic stability and response to disturbances such as faults. By utilizing BELBIC, power systems can achieve improved transient stability and faster response by dynamically adjusting control parameters and actions. The performance of an emotional controller and a conventional controller in voltage regulation is compared using MATLAB/Simulink simulations. A Plexim RT Box, a TI C2000 evaluation board, and PLECS software are used to complete the hardware-in-the-loop implementation of the closed controller and further evaluate the proposed controller. A three-phase ground fault is introduced into the system, and the outcomes demonstrate that the emotional controller swiftly stabilizes the system both during and after the fault is resolved.

The paper is organized as follows: In Section II, a third-order model of a single-machine infinite-bus power system is presented. The details of the emotional controller, BELBIC, are discussed in Sections III and IV. Results from MATLAB/Simulink simulations and HIL implementation of the proposed controller are provided in Sections V and VI, respectively.

II. Power System Dynamics

A simplified dynamic model of a power system, namely, a single-machine infinite-bus power system is considered in this paper [1,14,15]. The model includes a synchronous generator connected through a parallel transmission line to a very large power network approximated by the infinite bus.

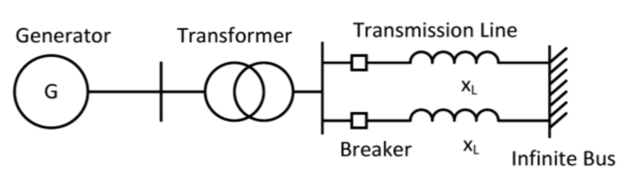

Figure1. Schematic of a single-machine infinite-bus power system.

The single-line diagram of the model is shown in Figure 1. The classic third-order single-axis dynamic model of the single-machine infinite-but power system can be written as follows [15], [16], [17]:

A. Mechanical equations

$$\dot{\delta}(t) = \omega(t) - \omega_{syn} \quad (1)$$

$$\dot{\omega}(t) = -\frac{D}{2H}(\omega(t) - \omega_{syn}) - \frac{\omega_{syn}}{2H}(P_e(t) - P_m) \quad (2)$$

Remark 1: Since the governor's action is slow enough not to have any significant impact on the machine dynamics, it is assumed that the mechanical input power P_m is constant.

B. Generator electrical dynamics

$$\dot{E}'_q(t) = \frac{1}{T'_{do}}(E_f(t) - E_q(t)) \quad (3)$$

C. Electrical equations (assumed $x'_d = x_q$)

$$E_q(t) = E'_q(t) + (x_d - x'_d)I_d(t) \quad (4)$$

$$E_f(t) = k_c u_f(t) \quad (5)$$

$$P_e(t) = \frac{E'_q(t)V_s}{x'_{ds}}\sin\delta(t) \quad (6)$$

$$I_d(t) = \frac{E'_q(t) - V_s\cos\delta(t)}{x'_{ds}} \quad (7)$$

$$I_q(t) = \frac{V_s}{x'_{ds}}\sin\delta(t) \quad (8)$$

$$Q(t) = \frac{E'_q(t)V_s}{x'_{ds}}\cos\delta(t) - \frac{V_s^2}{x'_{ds}} \quad (9)$$

$$E_q(t) = x_{ad}I_f(t) \quad (10)$$

$$V_t(t) = [(E'_q(t) - x'_d I_d(t))^2 + (x'_d I_q(t))^2]^{\frac{1}{2}} \quad (11)$$

The system parameters definitions are as follows:

$\delta(t)$	Power angle of the generator, radians
$\omega(t)$	Rotor Speed of the generator, radian/seconds
ω_{syn}	Synchronous machine speed, rad/seconds
P_m	Prime mover input mechanical power, p.u.
$P_e(t)$	Active electrical power delivery, p.u.
$Q(t)$	Reactive electrical power delivery, p.u.
$E_q(t)$	EMF in the quadratic axis of the generator, p.u.
$E'_q(t)$	Transient EMF of the generator, p.u.
$E_f(t)$	Equivalent EMF in the excitation coil, p.u.
$V_t(t)$	Generator Terminal Voltage, p.u.
$u_f(t)$	Input of the SCR amplifier of the generator, p.u.
V_s	Infinite bus voltage, p.u.
x_T	Reactance of the transformer, p.u.
x_d	Direct axis reactance of the generator, p.u.
x'_d	Direct transient axis reactance of the generator, p.u.
x_{ad}	Mutual reactance between excitation and stator coils

$x_{ds} = x_d + x_T + x_L,\ x'_{ds} = x'_d + x_T + x_L,\ x_s = x_T + x_L$

III. Emotional Controller Model

The primary objective of this research is to employ a structural model, inspired by the mammalian brain's limbic system, for control and decision-making purposes in power system stability and regulation. This approach is driven by the efficacy of emotion-based functional modeling in control engineering applications. The emotional controller is a computational model that simulates various brain regions, including the amygdala, orbitofrontal cortex, thalamus, and sensory input cortex, which are typically associated with emotion processing. This model is based on a network model developed by Moren and Balkenius [11]. There are two strategies for leveraging cognitive control and intelligence. The first, known as the "indirect approach", uses the intelligent system to fine-tune the controller's parameters. The second strategy, called the "direct approach", employs the intelligent system, in this case, the computational model BELBIC, as the controller block. BELBIC essentially generates actions based on emotional signals and sensory inputs. While these inputs can generally be vector-valued, for the sake of illustration, this paper considers only one sensory input and one emotional signal (stress) in the benchmarks used. Emotional learning primarily takes place in the amygdala, and the learning rule of the amygdala is as follows:

$$\partial V(t) = k_a \max(0, u_{EC}(t) - A(t)) \quad (12)$$

Where $V(t)$ is the gain in the amygdala connection, k_a is the learning step in the amygdala and $u_{EC}(t)$ and $A(t)$ are the values of emotional cue function and amygdala output. The formula (12) uses the term "max" to make the learning changes monotonic, implying that the amygdala gain can never be reduced. This rule is meant to resemble how the amygdala is unable to unlearn the emotion signal it previously learned, and as a result, emotional behavior. Similarly, the learning rule in the orbitofrontal cortex is shown in the formula (13).

$$\partial W(t) = k_o(y_{BEL}(t) - u_{EC}(t)) \quad (13)$$

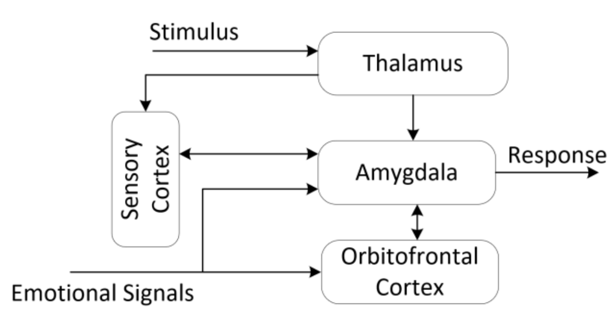

Figure 2. The structure of the Emotional Based Controller.

where $y_{BEL}(t)$ is the controller output, $W(t)$ is the gain in the orbitofrontal connection, k_o is the learning step in the orbitofrontal cortex. The output of the whole model, $y_{BEL}(t)$, can be calculated by subtracting the orbitofrontal output from the amygdala output as shown in the formula (14):

$$y_{BEL}(t) = A(t) - O(t) \tag{14}$$

in which, $O(t)$ represents the output of the orbitofrontal cortex.

The model receives the sensory input $u_S(t)$, uses the relations in (15) and (16) to compute the internal signals of the orbitofrontal cortex and amygdala, and finally produce the output.

$$A(t) = V(t)\, u_S(t) \tag{15}$$

$$O(t) = W(t)\, u_S(t) \tag{16}$$

The orbitofrontal cortex is responsible for inhibiting any inappropriate response because the amygdala is unable to unlearn any emotional response it has ever learned.

IV. Implementation of the Controller

Emotional learning-based controllers have demonstrated excellent robustness and uncertainty-handling capabilities, all while being straightforward to use. To utilize the version of the Moren-Balkenius model as a controller [11], it is noted that it essentially converts two sets of inputs into the decision signal as its output. This block, called BELBIC, is used in a suitable way to create a closed-loop configuration in the feed-forward loop of the entire system, ensuring that the input signals are interpreted correctly. The learning algorithm and the action selection mechanism used in functional implementations of emotionally based (or typically reinforcement learning-based) controllers were all implicitly implemented by the block at the same time [18], [19]. The structure of the control circuit implemented in this study is illustrated in Figure 3.

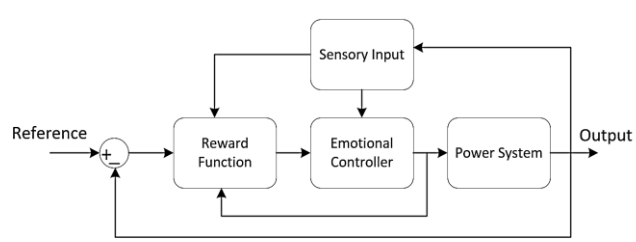

Figure 3. Closed-loop control system configuration of the emotional learning-based controller used as a voltage regulator for a power system.

The functions used in emotional cue and sensory input blocks are given in (17) and (18),

$$u_{EC}(t) = k_1 e(t) + k_2 \int e(t) + k_3\, y_{BEL}(t) \tag{17}$$

$$u_S(t) = k_4\, y_{out}(t) \tag{18}$$

where $e(t)$ and $y_{out}(t)$ are error signal, and plant output, and the k_1 through k_4 are the control gains that can be tuned for designing a satisfactory controller.

In the next two sections, the effectiveness of the emotional control scheme in maintaining power system stability is confirmed by examining its operation in a range of operational scenarios. Initially, the closed system simulations for voltage regulation are analyzed, followed by the hardware-in-the-loop implementation for fault-tolerant performance.

V. Simulation

Computer simulations of the closed-loop control are carried out using MATLAB/Simulink software. The parameters of the power system dynamics presented in Section II are considered as:

$$x_d = 1.863, x'_d = 0.257, x_T = 0.127, x_L = 0.4853$$
$$x_{ad} = 1.712,\ H = 4,\ D = 5,\ \omega_o = 314.159,\ k_c = 1$$
$$x_{ds} = 2.23265,\ x'_{ds} = 0.62665,\ x_s = 0.36965$$
$$T'_{do} = 6.9,\ \delta_o = 30^o,\ P_{mo} = 0.7,\ V_{to} = 1.1$$

The reference input voltage changes between 1 p.u. and 1.1 p.u. As shown in Figure 4, The requested reference voltage is being tracked by the emotional closed-loop control system. In the first transient period, the output voltage slightly overshoots, but as the controller learns and adapts, it eliminates the overshoot while maintaining the same rise time in the subsequent transient cycles. The results of the conventional well-tuned PI controller are provided for comparison which confirms that the emotional controller provides a better performance with lower overshot. The response of the system power angle, $\delta(t)$, is also depicted which confirms the output of the emotional controller has lower oscillation and faster response time.

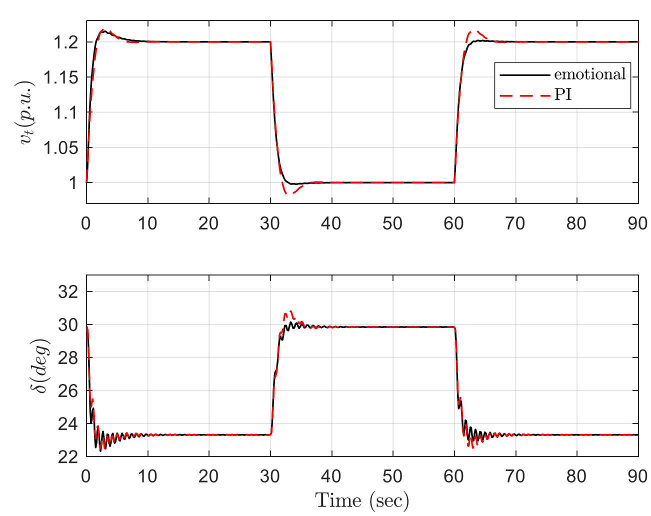

Figure 4. Performance of emotional vs traditional controller in reference voltage tracking.

Reactive and Active power produced by the generator is shown in Figure 5. The controller stabilizes the active power to the desired value of almost 0.7 p.u., while as expected the reactive power changes. Referring to equation (6), since terminal voltage, $V_t(t)$, changes, the controller changes the power angle, $\delta(t)$, to ensure constant active power delivered.

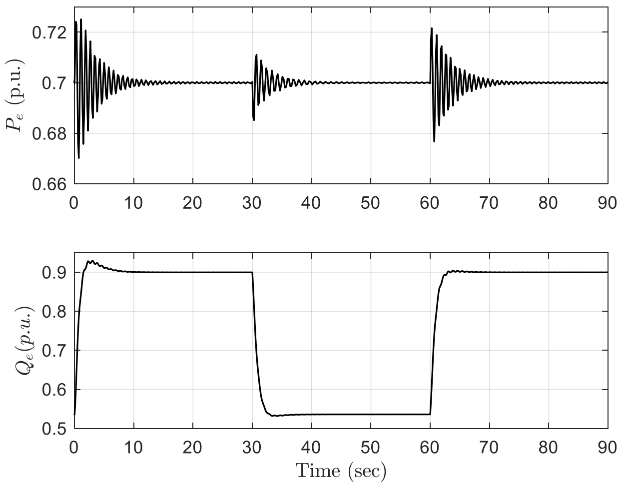

Figure 5. The active and reactive output power of the generator.

VI. HARDWARE-IN-THE-LOOP IMPLEMENTATION

The closed-loop control of the power system is implemented using a hardware-in-the-loop approach, utilizing the Plexim RT-Box system, PLECS software, and the Texas Instrument C2000 Evaluation board. The power system model is converted into executable code and transferred to the RT-Box for real-time simulation. This real-time system enables interaction with hardware through digital and analog I/O terminals and allows for the visualization of results within the software, thereby aiding in model refinement and testing.

Figure 6. Hardware-in-the-Loop setup consists of a Plexim RT Box, a TI TMS320F28379D Evaluation Board, a LaunchPad Interface, and a PC for code generation.

A TI C2000 evaluation board is used to execute the control system algorithm. Figure 6 shows the HIL implementation of the closed-loop power system. Since the regulation is studied through simulation and to better investigate the performance of the proposed controller, a symmetrical three-phase short circuit fault in the middle of one of the transmission lines with the following sequences occurs:

- The system is in the pre-fault steady state.
- A fault occurs at $t = 25$ seconds.
- The fault is removed 0.1 seconds later by a disconnected line.
- The system is in a post-fault state.
- The disconnected line is successfully reconnected after 1 second.

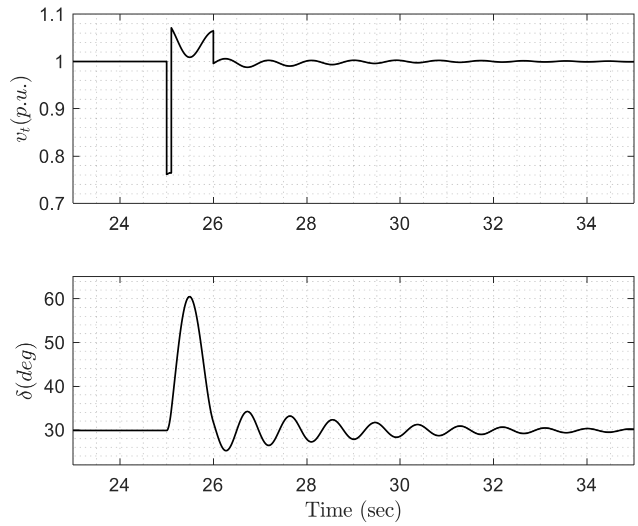

Figure 7. System performance in the event of a three-phase short circuit fault at t = 25 seconds.

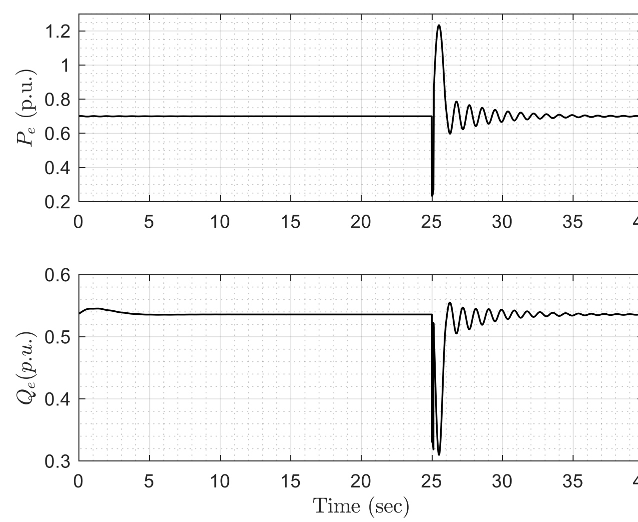

Figure 8. Active and reactive power variation in the presence of the three-phase ground fault.

The responses of the closed-loop system with the emotional controller in the presence of the aforementioned fault are depicted in Figure 7. It is evident that the terminal voltage of the synchronous generator is adjusted back to its pre-fault value, and the power angle demonstrates a significant stability margin, which is a desirable attribute in a power system. Hence, the emotional controller can retain the system stability while regulating the output voltage to the desired reference value. Figure 8 depicts the electrical output's active and reactive power. It is apparent that once the fault is cleared, the emotional controller promptly restores the output power to its target value, although with minor fluctuations.

VII. CONCLUSION

This paper introduces a novel controller designed for transient stabilization and voltage regulation within power systems. Employing an innovative intelligent controller known as BELBIC, inspired by mammalian limbic emotional learning algorithms, the study demonstrates its effectiveness through simulation studies and hardware-in-the-loop conducted on single-machine infinite-bus power systems. A comparative analysis with the conventional controller is provided, highlighting the unique flexibility of the emotional controller, characterized by its adjustable gains, which offer considerable freedom in tailoring the controller's response to desired specifications. Simulations and hardware-in-the-loop results confirm that the emotional controller has superior performance in voltage regulation and system stability.

VIII. REFERENCES

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