

Supervisory Controller Design for Power System Stability using Hybrid Automata Modeling

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Power systems are categorized as nonlinear dynamical systems, and the importance and complexity associated with their stability have dramatically increased. Accordingly, the behavior of power systems can be characterized by interactions between continuous and discrete-event dynamics. This paper proposes a systematic approach to the design and analysis of a supervisory control scheme for power systems using the hybrid automata (HA) model. The proposed model for optimal controller application is derived, and the power system's overall behavior is modeled using HA to enhance its stability. Hybrid systems' formulation incorporates continuous dynamics as well as discrete switching behavior into a modeling and control framework, thus allowing a complete system description while crystallizing the concepts of safety into system design criteria. This study uses a power system (HA) model as a discrete event system (DES) plant and controller. In the proposed method, to present the hybrid model, the discrete events used include the presence and absence of disturbances and voltage control elements, fault, sudden load increase, capacitor bank, and under-load tap changer (ULTC) transformer. Voltage stability and control are investigated by the generators' rotor angle, bus voltage, eigenvalues, and the stability theory of the switched linear systems. Applications in voltage control, stability, and dynamic service restoration are presented on two benchmark power systems with 12 discrete states. The simulation results reveal the effective performance of the proposed supervisory controller model to enhance voltage stability in power systems.

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I. INTRODUCTION

To maintain the operating range of the equipment, stability and voltage control in power systems are inevitable and have been a major topic in this domain. In electrical distribution systems, for voltage stability, reactive power generation devices (e.g., static reactive power compensators), as well as under-load tap changer (ULTC), are utilized. In these cases, the ULTC transports the voltage within the acceptable range and, then, the static reactive power compensator is responsible for its precise control [1].

Various methods are adopted for voltage control and power system stability. Due to the power system's nonlinear

behavior, hybrid modeling can be employed to design supervisory controllers. Power systems can be modeled with a hybrid automatic model because their behavior is described by interactions between continuous dynamics and discrete events [2]. HA modeling is suitable for simple power systems [2], [3]. Considering the discrete conduction mode of most electrical power system equipment used for switching, voltage regulation, etc., such as switches, which are discrete on or off [2], different methods of descriptive language (e.g. fuzzy logic, Petri net, automata) are applied to represent a DES system. Ref. [4] deals with the fault diagnosis of a linear continuous-variable dynamical system represented by a discrete state-space model. The proposed fault diagnoser is based on a special Petri Net called continuous-time delay Petri net (CTDPN). In general, stability is a feature of the power system that allows it to remain in the equilibrium

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mode under normal conditions and/or allows the system to reacquire an admissible mode under disturbance [1]. Stability is frequently discussed in terms of maintaining the performance of synchronous generators [1].

Since power generation in a power system is based on synchronous generators, all machines must be operated in synchronous mode or in harmony with one another to achieve satisfactory system performance. This aspect of stability is influenced by the dynamics of the generator's rotor angle equation [1]. Moreover, rotor angle stability and short-term voltage stability are closely linked to each other. In some cases, the loss of synchronism of any generator in the power system may lead to short-term voltage instability or collapse [5]. Therefore, the rotor angle must be checked via a certain threshold to ensure rotor angle stability [5].

When evaluating stability, it is essential to consider the system's behavior when it is operated under a transient disturbance [1]. The system must resist severe disturbances including a short circuit on a transmission line, loss of a generator or a large load, and/or loss of communication between two subsystems [1], [6]. The system's performance under disturbances is mainly influenced by the performance of its components [1], [6].

In [7], a controller design method has been developed using the hybrid automaton approach for a three-phase switch shunt active power filter (SAPF) supplied by a photovoltaic system and associated with the nonlinear load. In [8], besides designing a controller to coordinate the performance of two VSEs, including a ULTC-equipped transformer and static VAR compensator (SVC), problems related to the practical implementation of the controller are presented, and recommendations are made on transformer and compensator controller settings and synchronization between control systems; however, in this study, we used the hybrid modeling method to control and maintain voltage stability. The theory of discrete event systems (DES) monitoring is proposed to address power system problems such as challenges of controlling the voltage of ULTC-equipped transformers, which are extensively used in transmission systems to protect instantaneous load changes.

In [9], an innovative supervisor localization technique has been utilized to solve the voltage control problem in a distributed method that has a simpler and more transparent structure than the supervisory control method utilized in the present study. Moreover, the voltage decay in power systems is examined to study the voltage decay, and techniques related to voltage stability are summarized [10].

In [11], the role of distribution grid control against a steady voltage has been examined in a case study. Furthermore, in [12], a robust PI controller is designed to reach the desired control objective. The robustness of PI is guaranteed by the Lyapunov stability theory.

Methods available to analyze voltage stability include those

based on power flow Jacobian matrix as the minimum eigenvalue [13], test function [14], tangent vector [15], Markov chain's probability [16], indices determined by Lagrange multipliers [17], Jacobian matrix singularity, small disturbance voltage stability (SDVS) [18], and bus voltage ranking index [19], [20].

Therefore, for an easier analysis of stability and voltage regulation, followed by the supervisory controller design, the automatic hybrid modeling formulation is employed in this paper. In this way, the space state and transfer function are obtained. After this step, system stability can be easily evaluated. In the proposed method, to present the hybrid model, discrete events, including the presence and absence of disturbances and voltage control elements, fault, sudden load increase, capacitor bank, and ULTC transformer, are used.

Herein, voltage stability is examined for five system modes. In Sections III and IV, first, two scenarios of $Sm(F,T,C)$ and $Sm(L,T,C)$ are defined in which definitions are presented for various system modes (Sm). The controller is designed by hybrid automata (HA) modeling in power systems under disturbance resulting from fault (F) and a sudden increase in load (L). The supervisory controller is designed using ULTC (T) and a capacitor bank (C). The discrete events system (DES) is presented, and then the overall HA modeling for each system consisting of 12 modes is performed.

The simulation results show that the voltage control process is implemented and examined by applying the disturbance caused by a fault and a sudden increases in load for a WSCC 9-bus and IEEE 30-bus system using Matlab and Digsilent; a supervisory controller is also designed in the presence of disturbance resulting from a three-phase fault to earth and a sudden increase in load. Finally, the voltage stability in the controller is examined using four approaches of "buses' voltage", "generators' rotor angle", "the eigenvalues of the system", and "the stability theory of the switched linear systems". Simulation results demonstrate that the proposed using HA modeling is easier and more accurate for power system voltage stability.

The rest of this paper is organized as follows: Section II describes the hybrid system and hybrid automata (HA). In Section III, voltage stability is examined for five system modes. Section IV presents the proposed HA modeling for two scenarios of $Sm(F,T,C)$ and $Sm(L,T,C)$. A supervisory controller for two scenarios is also designed. In Sections V and VI, simulation results are discussed. Finally, in Section VII, the conclusions derived from this work are presented.

II. HYBRID SYSTEMS

The introduction of the supervisory control theory (SCT) provided the necessary background for applying discrete event models (DEMs) to the processes of the physical world; consequently, a wide range of industrial systems, including

traffic control systems, manufacturing line systems in industrial plants, telecommunication systems, database systems, and electrical power systems have been studied [21]. A hybrid dynamic system is a system whose behavior is influenced by continuous and discrete dynamics. As an important feature of hybrid systems, some dynamics are time-driven while some are event-driven. In time-driven systems, the mechanism of the system mode change is based on differential equations where the modes vary over time. In event-driven and DES systems, changes in the system mode depend on the events that occur, not the time [21], [22].

The continuous system is usually a physical and natural system with a continuous behavior. The communication between two continuous and DES systems is facilitated by an interface and the use of communication signals. Some major types of hybrid dynamic systems include the HA machine, timed Petri nets, and switched systems [22].

A. Hybrid Automata (HA)

Hybrid automata (HA) machines provide a general modeling formulation for the analysis of hybrid systems. HA is utilized to model dynamic systems which include both continuous and discrete components [22].

HA can be expressed as an eight-parameter relation as follows [22]:

$$H = (Q, \nu, f, \text{Init}, \text{Inv}, \theta, G, R)$$

- Q is a limited set of discrete modes (control locations) of the system; $Q = \{q_1, \dots, q_k\}$, $q \in Q$;
- ν refers to a limited set of continuous states of the system, and X is the continuous state space;
- $\dot{x} = f(q, x)$ is the continuous dynamics, and f denotes the functions related to the continuous dynamics of the system $(q, x) \in Q \times \nu$;
- $\text{Init} \subseteq Q \times R^n$ is a set of the system's initial modes and conditions;
- $\text{Inv} : Q \rightarrow 2^{R^n}$ is the description of the characteristics of locations; it is, in fact, a prerequisite for staying in or passing the continuous modes of the system. As long as the prerequisite related to each location is mandatory, there is a continuous dynamic for that location and it can operate.
- $\theta \subseteq Q \times Q$ is the interface of the system's transitions graphically depicted as arcs between discrete modes.
- $G : \theta \rightarrow 2^{R^n}$ is the system guard prerequisite; it constrains the continuous dynamics' function. The prerequisite is applied to the arcs of the HA model.
- $R : \varepsilon \rightarrow 2^{R^n} \times 2^{R^n}$ resets the map to its initial mode.

Based on this mapping, one can find the location of the continuous state in the subset of the continuous state space that is not used in the power system [22].

III. EXAMINING VOLTAGE STABILITY OF POWER SYSTEMS WITHOUT A CONTROLLER

When evaluating stability, it is essential to consider system behavior when it is operated under a small or large transient disturbance. Disturbances applied to the grid in this study include:

I) *Three-phase fault to Earth on the most sensitive bus of the grid*

The most sensitive bus is sensitive to sudden voltage changes and makes the network/grid unstable.

II) *A sudden increase in load*

In this section, voltage stability is examined for five system modes:

- Under normal circumstances
- In the presence of a fault in the grid
- In the presence and absence of a fault and change in the tap changer
- In the presence and absence of a fault and a sudden increase in load
- In the presence and absence of a fault and a capacitor bank

The methods used to monitor system stability include:

- a) The voltage of the busses [1], [23] and [24].
- b) The rotor angle of generators [1], [23].
- c) The eigenvalues of a system [1], [23] and [25].
- d) The stability theory of the switched linear systems [26], [27] if the controller is present.

According to previous studies, in the absence of a controller, system stability is examined in three ways "a", "b" and "c", while in the presence of a controller, system stability is examined in four ways "a", "b", "c" and "d".

IV. HYBRID AUTOMATA CONTROLLER DESIGN AND MODELING

The purpose of designing a controller for a grid is to provide stability and voltage control. Controller inputs include the voltage of the most sensitive bus of the grid and ULTC.

i) The voltage of the most sensitive bus of the grid; the control of the ULTC T tap changer status is adjusted to the voltage of the most sensitive bus. The standard voltage deviation of buses is 5%, i.e. A bus voltage of $1.05 < V_{bus} > 0.95$ is standard and permitted [1], [28].

ii) The ULTC tap changer has state "3"; for each increase in the tap changer, a 3% increase in voltage is applied to the grid.

A bus voltage < 0.95 indicates a voltage drop on the bus. Some important controller functions include:

- After applying the fault to the most sensitive bus, the system becomes unstable and a voltage drop occurs in the grid [23]. As a result, the tap changer first shifts from state 1 to state 2, and then (if the drop in voltage occurs again in the

system or under instability) shifts to state 3.

- If the tap changer is in state 3 and there is also a drop in voltage, or when the system is unstable, then the tap changer remains in state 3.
- The voltage of the most sensitive bus is > 1.05 , $V_{bus} > 1.05$ and a stable system puts the capacitor bank out of the circuit.
- When the tap changer is in state 3 and the bus voltage is > 0.95 , $V_{bus} > 0.95$, this indicates that there is no voltage drop in the system. Therefore, the tap changer returns to state 2. If there is no voltage drop again, the tap changer will return to state 1 (initial mode).

A. Modeling of HA and the performance of a supervisory controller under the disturbance caused by a three-phase fault to Earth

For HA modeling, discrete states of the system are first introduced; these are a combination of discrete events, including disturbance resulting from fault, in the presence and absence of a fault, in the presence and absence of voltage control elements such as a capacitive bank, and an increase and decrease in ULTC tap changer with three states (Table I).

TABLE I
DESS WITH THE SCENARIO OF SM (F, T, C)

Event Name	Value	Explanation of an event
F	1	Presence of a fault
	0	Lack of a fault
T	1	State of tap trans 1
	2	State of tap trans 2
	3	State of tap trans 3
C	1	Presence of a capacitor
	0	Lack of a capacitor

The power system is represented by the symbol S and the mode number m. If the combined modes of the system are defined as $Sm(F,T,C)$ scenario, then all the combined states occurring for the system include 12 modes as presented in Table II.

TABLE II
SYSTEM MODES WITH SCENARIO SM (F,T,C)

Sm	F	T	C
S1	0	1	0
S2	0	1	1
S3	0	2	1
S4	0	3	1
S5	1	1	1
S6	1	2	1
S7	1	3	1
S8	0	2	0
S9	0	3	0
S10	1	1	0
S11	1	2	0
S12	1	3	0

Each mode has a specific continuous dynamic. For example, mode "S3" represents the continuous dynamics of the system with the presence of faults, the tap changer in status 2, and in the absence of capacitors in the grid.

According to Fig. 1, the system initially operates in the normal condition (initial state of the system S1) under a constant voltage and the desired amplitude (voltages of all buses are > 0.95). The system remains in the S1 state until the fault is applied to the system (i.e. $F = 0$); when the fault is applied to the most sensitive bus of the system (i.e. $F = 1$), the system tends to become unstable and shifts from S1 to S2. To improve the voltage of buses and the grid stability, the T tap changer increases again and shifts from status 1 to state 2, i.e. It shifts to state S3. In the event of instability, the T tap changer increases again and shifts from status 2 to state 3, i.e. It shifts to state S4. Constant system instability puts the capacitor bank into the circuit, i.e. The system shifts to state S7. After removing the fault (i.e. $F = 0$), the system shifts to state S12, and then, it reaches its initial state; it first puts the capacitor bank out of the circuit, and the system shifts to state S9; then, the T tap changer shifts from state 3 to state 2 while the system shifts to state S8; finally, the tap changer shifts to state 1, the system returns to its initial state, and the voltage of all buses reaches > 0.95 . Fig. 1 displays the HA model of the closed-loop system..

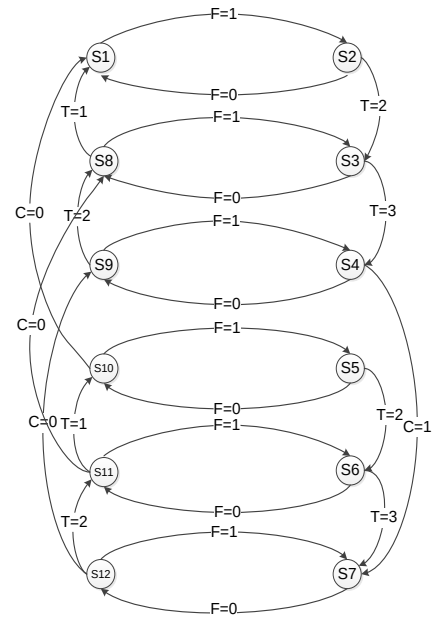


Fig. 1. HA model of the $Sm(F,T,C)$ scenario

The HA model of the system is an eight-parameter [22] relation (Equ. (1)).

$$H = (Q, v, f, Init, Inv, \theta, G, R) \quad (1)$$

Q is a set of discrete states of the system as presented in Table II and in Equ. (2):

$$Q \in \{S1, S2, S3, S4, S5, S6, S7, S8, S9, S10, S11, S12\} \quad (2)$$

v is a set of continuous variables of the system as shown in Equ. (3) and defined in the DIGSILENT software [29]:

$$v \in \{\phi, speed, psie, psiD, psiX, psiQ\} \quad (3)$$

Descriptions of continuous variables are provided in Table III.

TABLE III
CONTINUOUS VARIABLES [29]

Name of variables	Name of Unit	Explanation
Speed	p.u	speed
Phi	rad	Rotor angle
Psie	p.u	Excitation Flux
PsiD	p.u	Flux in D - Winding
Psix	p.u	Flux in X - Winding
psiQ	p.u	Flux in Q - Winding
Speed	p.u	speed

In steady-state systems, the eigenvalues are obtained by Modal Analysis in Digsilent. After that, the transfer function will be obtained.

The continuous dynamics of the system can be represented as $\dot{x} = A_i(x)$, including the continuous equations of each of the 12 states of the system. To obtain A_i in Equ. (4), given the eigenvalues corresponding to each state, the denominator of the transfer function for the system $P_i(S)$ is obtained by Equ. (5). Then, the matrices A of each state of the system are obtained by the canonical realization of its controller (explained in Appendix A).

$A_i \in \{A_1, A_2, A_3, \dots, A_{12}\}$, $i = 1, 2, \dots, 12$ and i stands for the number of these states

(4)

$$A_i = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & \dots & 1 \\ -a_0 & -a_1 & -a_2 & \dots & -a_{n-1} \end{bmatrix}$$

$$P_i(S) = S^n + a_{n-1}S^{n-1} + \dots + a_1S + a_0 \quad (5)$$

n is the number of eigenvalues;

$$\text{Inv} \in \{F=0, F=1\} \quad (6)$$

Inv is expressed according to Equ. (6); for example, the system first operates in the normal condition (initial state; S1) under constant voltage and optimal amplitude. The initial state of the system is expressed as $\text{Init} = S1$.

System guards, under the same prerequisite intended for the HA arcs, are expressed as Equ. (7).

$$G \in \{F=0, F=1, C=0, C=1, T=1, T=2, T=3\} \quad (7)$$

B. Modeling of HA and the supervisory controller performance under disturbance caused by a sudden increase in load

For HA modeling, discrete states of the system are first introduced; these are a combination of discrete events, including disturbances caused by a sudden increase in load and without a sudden increase in load (normal condition for load), the presence and absence of voltage control elements such as a capacitive bank, and the increase and decrease of the ULTC tap changer with the three states (Table IV).

TABLE IV
DESS WITH THE SCENARIO Sm(L, T, C)

Event name	Value	Explanation of an event
L	1	sudden increase of load
	0	Lack of a sudden increase of load
T	1	State of tap trans 1
	2	State of tap trans 2
	3	State of tap trans 3
C	1	Presence of a capacitor
	0	Lack of a capacitor

Combined modes of the system are defined as the Sm(L,T, C) scenario. Overall, all the combined modes occurring for the system constitute 12 separate modes (Table V).

TABLE V
SYSTEM MODES WITH SCENARIO Sm(L,T,C)

Sm	L	T	C
S1	0	1	0
S2	0	2	0
S3	0	3	0
S4	0	1	1
S5	0	2	1
S6	0	3	1
S7	1	1	0
S8	1	2	0
S9	1	3	0
S10	1	1	1
S11	1	2	1
S12	1	3	1

The controller consists of 12 discrete modes, each with a special continuous dynamic. The system first operates in the normal condition (initial state of the system; S1) under constant voltage and optimal amplitude (all bus voltages are $s > 0.95$). After a sudden rise in load at one of the most sensitive loads of the grid, the system shifts to the S7 mode. To improve bus voltage and grid stability, the T tap changer increases and shifts from state 1 to state 2, i.e. The system shifts to state S8. If the bus voltage does not improve, the T tap changer will rise again and shift to state 3, i.e. The system shifts to state S9. Constant voltage drop puts the capacitor bank in the circuit, i.e. The system shifts to state S12. Improving the bus voltage puts the capacitor bank out of the circuit ($C = 0$); this causes the system to first shift to state S9 and then (if necessary) state S8; and finally, the T tap changer reaches status 1, i.e. The system shifts to state S7. HA modeling is performed for a scenario consisting of 12 system modes. The HA graph for the Sm(L,T,C) scenario is presented in Fig. 2.

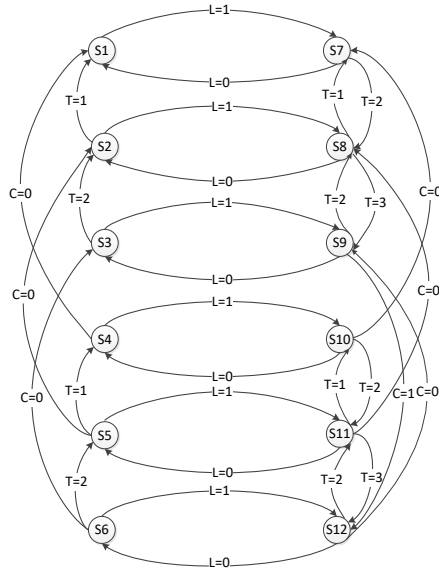


Fig. 2. HA model of the Sm(L,T,C) scenario

The continuous dynamics of the system can be represented as $\dot{x} = A_i(x)$, including the continuous equations of each of the 12 system states. To obtain A_i in Equ. (4), the denominator of the transfer function $P_i(S)$ for the system is obtained by Equ. (5). Subsequently, the matrices A of each state of the system are obtained by the canonical realization of its controller (Section A, and explained in APPENDIX A.).

$$\text{Inv} \in \{L=0, L=1\} \quad (8)$$

Inv is expressed by Equ. (8). First, the system operates in a normal condition (initial state; S1). The system remains in the S1 state until a sudden rise in load is applied (i.e. $L = 0$). If there is a sudden increase in load in the system ($L = 1$) and when the tap changer is in status 3 and there is a capacitor ($C = 1$) i.e. in state S12, then the unstable system will remain in instability because the tap changer is in status 3 and the capacitor is available. Nevertheless, if a sudden increase in load is removed ($L = 0$), then the system shifts to state S6 and becomes stable. The initial state of the system is expressed as $\text{Init} = S1$. System guards are expressed as Equ. (9).

$$G \in \{L=0, L=1, C=0, C=1, T=1, T=2, T=3\} \quad (9)$$

The hybrid modeling method applies to all power systems; for example, in this study, we implemented and simulated the method for the 9-bus power system.

V. SIMULATION RESULTS FOR FIRST CASE STUDY

The power system studied is a standard WSCC 9-bus, three-machine system. Fig. 3 illustrates the status of machines and buses and all impedances and admittances (in p.u.) [28]. The data of the system are given in APPENDIX A, TABLE XI.

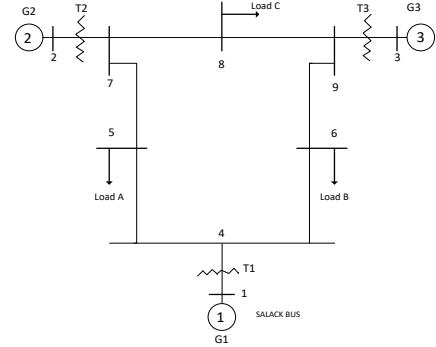


Fig. 3. standard WSCC 9-bus, three-machine system [28]

A. Maintaining the 9-bus system's voltage without a controller

The stability of the system is investigated for five modes, according to Sections III and B. According to [23], the fault was applied to bus 7 because it is the most sensitive bus to sudden voltage changes and can cause grid instability. The fault was applied to bus 7 at $t_s = 0.1$ sec. It has been demonstrated that a sudden increase in load A will drive a voltage drop in the grid buses [24]. The stability of the system was investigated in the four manners presented in Section III. It was found that, in the stable mode, the system is unstable in all cases in the presence of a fault in bus 7 and will no longer be stable even in the presence of a capacitor bank. In steady-state, each system mode has its continuous equations and is considered as a discrete state for a hybrid system. The results of examining the stability of the 9-bus system are presented in Table VI.

TABLE VI
RESULTS OF EXAMINING THE STABILITY OF THE 9-BUS SYSTEM WITHOUT A CONTROLLER

States of system	Voltage of buses, p.u.	Stability of steady and transient state	Explanations
Normal system	$V_{bus} > 0.95$	Stable	No voltage drop
Increase of tap trans	$V_{bus} > 0.95$	Stable	No voltage drop
Activity of capacitor	$1.05 < V_{bus} > 0.95$	Stable	No voltage drop
Sudden increase of Loads	A few buses less than 0.95	Stable	Small voltage drop in buses
Five mentioned states with presence of fault	$V_{bus} < 0.95$	Instable	Severe voltage drop in the busses

B. Simulation results and examining voltage control under a disturbance caused by a three-phase fault to Earth from the Sm(F,T,C) scenario

Responses were evaluated by simulation in DIGSILENT. Under normal circumstances, the system maintains its steady state because no faults are applied to the system. The following events are applied to the system to monitor how the voltage is controlled. The ULTC tap controller is intended for

transformer T2.

Transformer T2 has a three-mode tap with a 3% rise in voltage at each phase of tap change. In $t=3$ sec, a three-phase fault-to-Earth fault is applied to the 7th bus for 1 second.

Capacitor placement is fulfilled via the genetic algorithm to minimize total loss. Load A is the optimal place to install the capacitor, where the grid has the least losses.

At $t=4$ sec, a 100MVar capacitor bank is applied to the grid in two 50MVar capacitance steps in the 5th busbar and close to Load A. Grid stability is now examined using a capacitor and a three-phase tap changer controller in the grid. System stability is evaluated by four approaches, including “buses’ voltage”, “generators’ rotor angle”, “the eigenvalues of a system”, and “the stability theory of the switched linear systems”.

I) Bus Voltage

When the fault is applied, the bus voltage drops; the bus voltage improves and the system reaches a stable mode after putting the capacitor in the grid (at $t=4$ sec), applying 107.17 MVar of reactive power into the grid and controlling voltage by changing the T2 tap changer (Fig. 4).

After applying the fault, the buses’ voltage is improved by the ULTC supervisory closed-loop controller system (Table VII).

In [30], an energy margin constrained online coordinated voltage control (CVC) algorithm was defined. The energy function model was established based on the detailed device models that included the effects of shunt capacitor banks, reactive power output of generators, and under-load-tap-changers (ULTCs). To control the voltage, the control equipment was checked separately. The simulation results for the three-machine system showed that in CVC method, by applying the fault to bus 3, voltage controls were performed using each of the capacitor banks and ULTC [30]. The average voltage of bus 3 was 1.012 p.u and 0.82 p.u in the presence of capacitive banks and ULTC, respectively. In the HA method, the voltage of all buses was in the steady state and above 1p.u., so comparing the HA and CVC methods showed that the HA method was more effective in voltage improvement.

TABLE VII

BUSES’ VOLTAGE OF SYSTEMS AND ITS SCENARIO Sm(F,T,C)

Name of bus	normal system, p.u	without controller, fault in Bus 7, p.u	within ULTC and capacitor, Sm(F,T,C), p.u
Bus 1	1.04	0.717	1.04
Bus 2	1.025	0.194	1.025
Bus 3	1.025	0.202	1.025
Bus 4	1.063	0.595	1.043
Bus 5	0.996	0.565	1.044
Bus 6	1.013	0.417	1.042
Bus 7	1.026	0	1.04
Bus 8	1.016	0.063	1.035
Bus 9	1.032	0.153	1.043

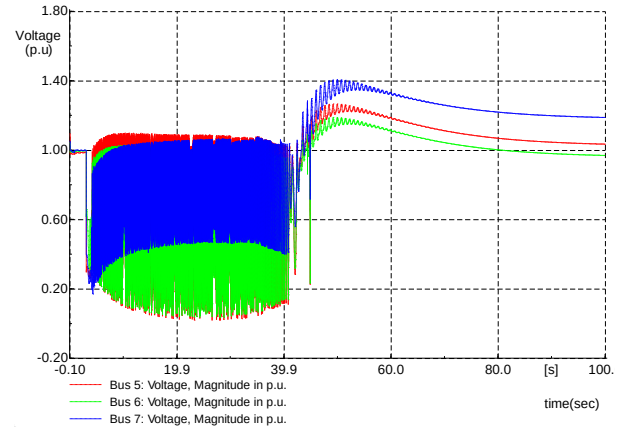


Fig. 4. Voltage of the system’s buses 5, 6, and 7 after applying the fault, with a controller

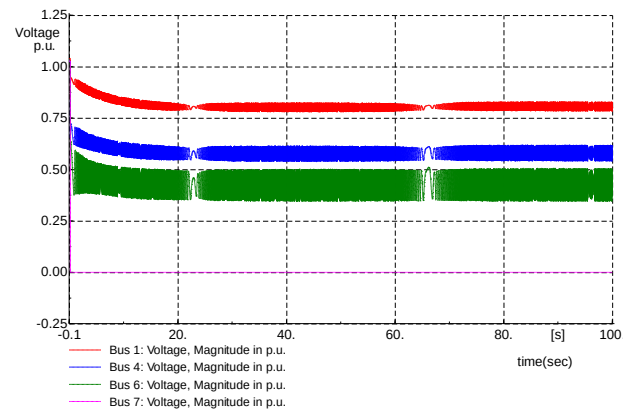


Fig. 5. Voltage of the system’s buses 1, 5, 6, and 7 after applying the fault, without a controller

At $t=3$ sec, when the fault is applied to the 7th bus, the bus voltage drops, and the tap changer first shifts to status 2 and then status 3 (its highest level). From the 3rd sec to about 40th sec, when the capacitor is also applied to the grid, the bus voltage oscillates and the tap changer shifts from status 2 to status 3. After the 40th sec, the voltage of the system’s buses improves and the tap changer returns to status 1, i.e. The voltage is controlled by the ULTC (Figs. 4 and 6).

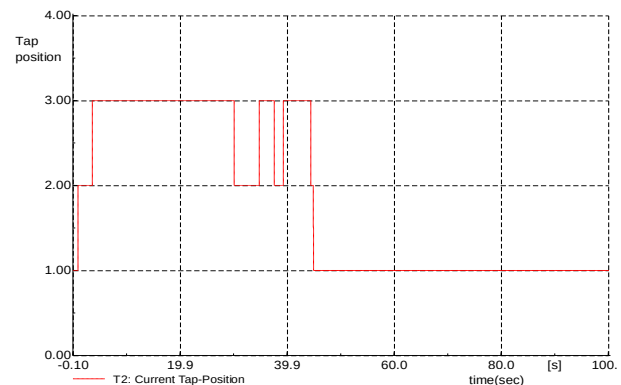


Fig. 6. Tap changer TC changes (T2), with a controller

II) Generator's rotor angle

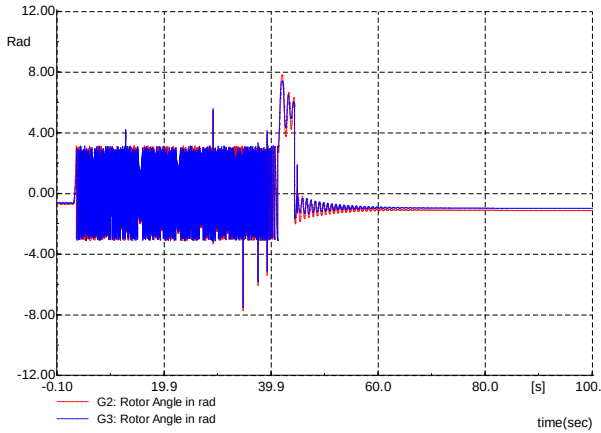


Fig. 7. Rotor angle of generator G3,G2, with a controller

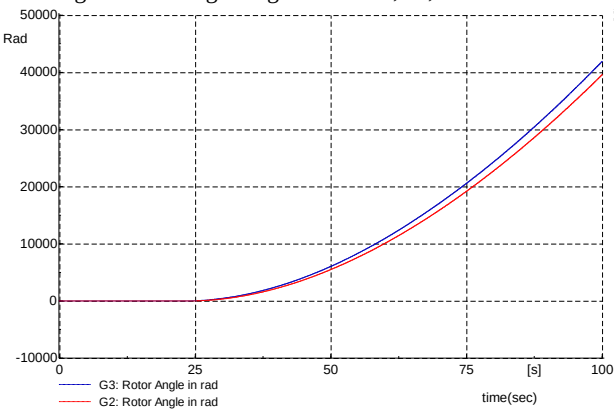


Fig. 8. Rotor angle of generator G3,G2, without a controller

Between $t=3$ sec, when the fault is applied to the 7th bus, to about the 40th sec, the rotor angle of the generators oscillates; after the 40th sec, the rotor angle of the generators will damp over time, indicating the stability of the system (Fig. 7).

III) The eigenvalues of a system

The eigenvalues of the system having a negative true root indicate the stability of the system at a steady state.

TABLE VIII
THE EIGENVALUES OF THE SYSTEM

Row	Eigenvalue	Row	Eigenvalue
1	0	10	-13.006
2	-55.519	11	-13.206
3	-37.196	12	-4.110
4	-0.744+j13.852	13	-2.805
5	-0.744-j13.852	14	-0.099+j0.049
6	-0.015+j9.409	15	-0.099-j0.049
7	-0.015-j9.409	16	-0.172
8	-15.217	17	-0.140
9	-11.704		

The results of controller simulation using the HA model, examining the voltage response of the buses, and considering the rotor angle of the generators show that the system is also stable in a transient state.

IV) The stability theory of the switched linear systems

According to theory 1 provided in [26] about the stability of a switched linear system, if some subsystems are stable while others are not, then to achieve overall stability, the duration of system operation in stable modes must be longer than the

duration of operation in unstable modes; this depends on the system's working growth and decline rate in unstable and stable modes [26], [27]. According to the above theory and given that the system has a longer operating time in the stable mode, it can be conservatively concluded that the entire system is stable.

C. Simulation results and examining voltage control under disturbance caused by a sudden increase in load from the Sm (L,T,C) scenario

Responses were evaluated by simulation in DlgSILENT. A 9-bus power system was considered with a three-phase T2 tap changer and a 3% increase in voltage at each step of tap change.

A 100MVar reactive power compensation capacitor bank is applied to the grid in two 50MVar capacitance steps in the 5th busbar and close to Load A. After simulating at $t=100$ sec, at the 0.013th sec, the active power of load A increases by 25% while the reactive power of load A suddenly increases by 5%; the situation puts the capacitor bank into the circuit for reactive power compensation.

When the load rises suddenly, the buses' voltage first drops, and the tap changer shifts to status 3; after putting the capacitor bank into the circuit, the buses' voltage improves (reaches > 0.95 p.u.) and the tap changer returns to status 1 (Table IX).

The system stability is measured by four approaches, including "buses' voltage", "generators' rotor angle", "the eigenvalues of a system", and "the stability theory of the switched linear systems".

I) Buses Voltage

After performing load distribution calculations, the buses' voltage somewhat drops in the Sm(L,T,C) scenario due to disturbances; it is possible to address the problem using reactive power control equipment (Table IX).

TABLE IX
BUSES' VOLTAGE OF NORMAL SYSTEMS AND ITS SCENARIO SM-(L,T,C)

Name of bus	Voltage of bus, normal system, p.u	Voltage of bus, without controller, p.u	Voltage bus within Sm(L,T,C), p.u
Bus 1	1.04	1.006	1.008
Bus 2	1.025	0.92	0.957
Bus 3	1.025	0.91	0.973
Bus 4	1.063	0.98	0.999
Bus 5	0.996	0.933	0.983
Bus 6	1.013	0.91	0.979
Bus 7	1.026	0.964	0.983
Bus 8	1.016	0.90	0.972
Bus9	1.032	0.95	0.985

At $t=0.013$ sec, load A suddenly increases by 25%, the buses' voltage drops first and, at $t=0.2$ sec, the capacitor bank enters the circuit and leads to the application of -38.6MVar reactive power into the grid; this improves the buses' voltage (Fig. 9).

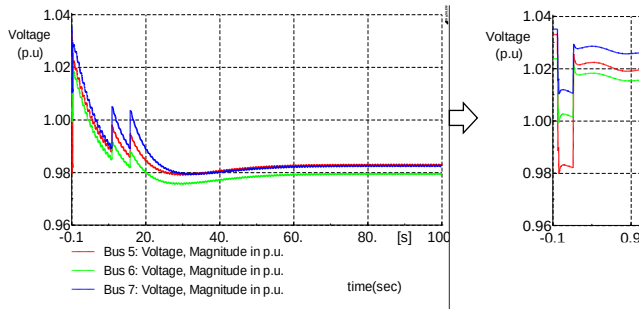


Fig. 9. Voltage of Bus 5, Bus 6, and Bus 7 of the system, with a controller (zoom -0.1 to 1 second)

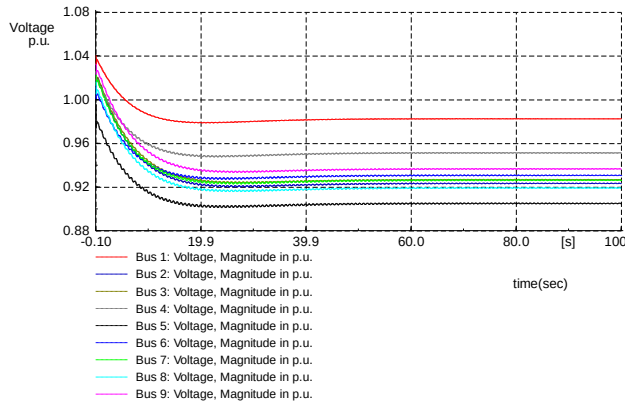


Fig. 10. Voltage of the system's buses, without a controller

As the buses' voltage drops, the tap changer shifts from status 1 to status 2 and then status 3. As the bus voltage improves while the capacitor is present, the tap changer remains in status 3 (Fig. 11).

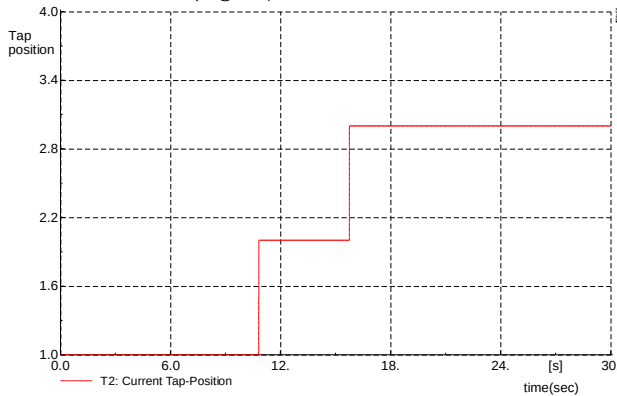


Fig. 11. Tap changer changes (T2), with a controller

II) Generators' rotor angle

At $t=0.013$ sec, the buses' voltage drops first and the rotor angle of the generators increases; then, the rotor angle of the generators dampens and converges while oscillating, indicating that the system is stable (Fig. 12).

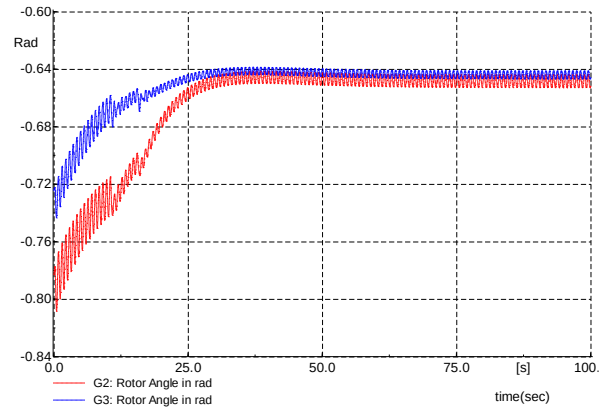


Fig. 12. Rotor angle of generators G2, G3, with a controller

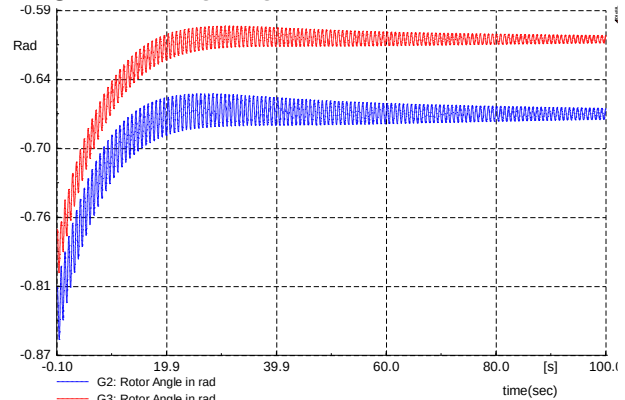


Fig. 13. Rotor angle of generators G2, G3, without a controller

III) The eigenvalues of a system

Considering the rotor angle of the generators as state variables, after calculations, 17 eigenvalues are obtained (Table X). The eigenvalues of the system having a negative true root indicate the stability of the system at a steady state.

TABLE X
THE EIGENVALUES OF THE SYSTEM

Row	Eigenvalue	Row	Eigenvalue
1	0	10	-12.98
2	-54.92	11	-13.2
3	-36.84	12	-3.92
4	-0.85+j13.81	13	-2.81
5	-0.85-j13.81	14	-0.2
6	-0.05+j9.29	15	-0.149
7	-0.05-j9.29	16	-0.108+j0.042
8	-15.20	17	-0.108-j0.042
9	-11.62	-	-

IV) The stability theory of the switched linear systems

As with paragraph IV of the controller, section B, according to prerequisite 1 in [26], and given that the duration of system operation in the stable mode is higher, it can be conservatively concluded that the entire system is stable.

VI. SIMULATION RESULTS FOR THE SECOND CASE STUDY

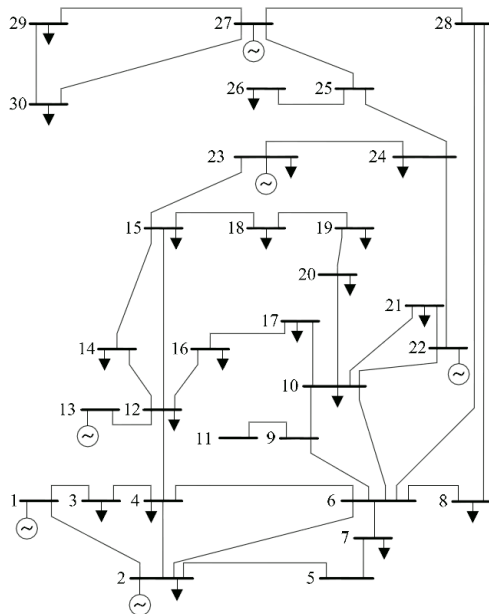


Fig. 14. IEEE 30-bus system [1]

the IEEE 30-bus system is illustrated in Fig. 14 with middle transmission lines, and the electrical property of each line is described by the model [1]. The simulation results of the stability analysis of the IEEE 30-bus system similar to the 9-bus system are presented in Table VI.

A. Simulation results and examining voltage control under a disturbance caused by a three-phase fault to Earth from the Sm(F,T,C) scenario

Responses were evaluated by simulation in DigSILENT. The following events are applied to the system to monitor how the voltage is controlled. The ULTC controller is intended for transformer Trf4.

Transformer Trf4 has a three-mode tap with a 3% rise in voltage at each phase of tap change.

Capacitor placement is fulfilled via the genetic algorithm to minimize total loss. By running the algorithm, the optimal place for installing the capacitor bank is obtained in Bus 10 and Bus 24 where the capacity must be 19 and 4.3 Mvar, respectively, to compensate for the reactive power. After fulfilling the simulation for a 30-sec time horizon, a three-phase to ground fault during the period of 0.1-0.5 seconds is imposed on Bus 28.

The grid stability is now examined using a capacitor and a three-phase tap changer controller in the grid. The stability analysis of the system in the presence of the supervisory controller is investigated from four aspects: buses' voltage, generators rotor angle, eigenvalues of the system, and the stability theorem of switched linear systems.

1) Bus Voltage

When the fault is applied, the bus voltage drops; the bus

voltage improves and the system reaches a stable mode after putting the capacitor in the grid (at $t=0.1$ sec), applying 19 and 4.3MVar reactive power into the grid, and controlling voltage by changing the Trf4 tap changer (Fig. 15).

After applying the fault, the buses' voltage is improved by the ULTC supervisory closed-loop controller system.

In [30], an energy margin constrained online coordinated voltage control (CVC) algorithm was defined. The energy function model was established based on the detailed device models that included the effects of shunt capacitor banks, reactive power output of generators, and under-load-tap-changers (ULTCs). The simulation results for the IEEE 30-bus system demonstrated that in CVC method, by applying the fault on lines 25–27 and lines 6-28, voltage controls were performed using the ULTC as well as both ULTC and capacitor [30]. In the HA method, the voltage of all the buses was in the steady state and above 1p.u., so comparing the HA and CVC methods represented that the HA method was more effective than the CVC method in voltage improvement (TABLE XI).

TABLE XI
COMPARISON OF COMPUTATION BUSES' VOLTAGE BY DEFFERENT METHODS FOR THE IEEE 30-BUS SYSTEM

Name of bus	proposed method(HA)		CVC method[30]	
	without controller, fault in Bus 28, p.u	within Sm(F,T,C), Capacitor and ULTC, p.u	ULTC, Line 25-27 tripping, p.u	Capacitor and ULTC, Line 6-28 tripping, p.u
Bus 05	0.16	1.03	1.01	1.01
Bus 06	0.08	1.032	1.01	1.02
Bus 07	0.11	1.035	1.01	1.01
Bus 08	0.1	1.032	1.00	1.01
Bus 23	0.08	1.031	1.01	1.01
Bus 24	0.07	1.037	0.99	1.025
Bus 26	0.04	1.021	0.98	1.012
Bus 30	0	1.02	1.01	1.001
Bus 38	0.03	1.02	1	0.99

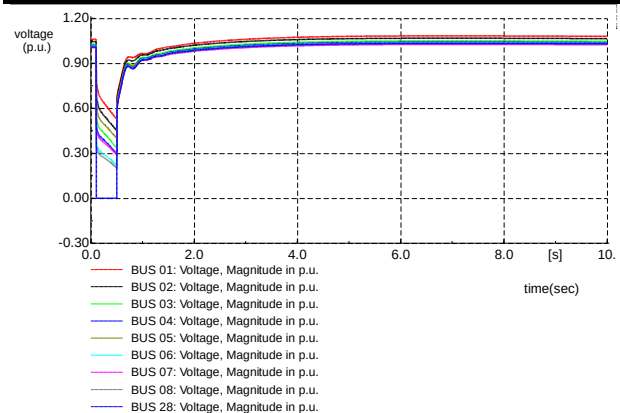


Fig. 15. Voltage of Bus 2 to Bus 8 and Bus 28 of the system, with a controller

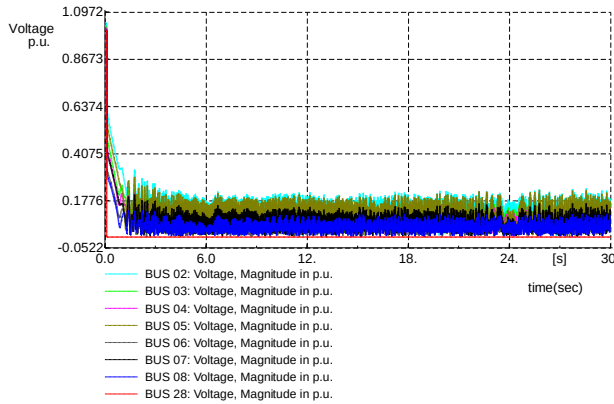


Fig. 16. Voltage of Bus 2 to Bus 8 and Bus 28 of the system, without a controller

Evidently, at $t=0.1$ sec, when the fault is applied to Bus 28, the bus voltage drops, and the tap changer first shifts to status 2 and then status 3 (its highest level). Subsequently, the capacitor is also applied to the grid. The voltage of the system's buses improves and the tap changer returns to status 1, i.e. The voltage is controlled by the ULTC (Figs. 15 and 17).

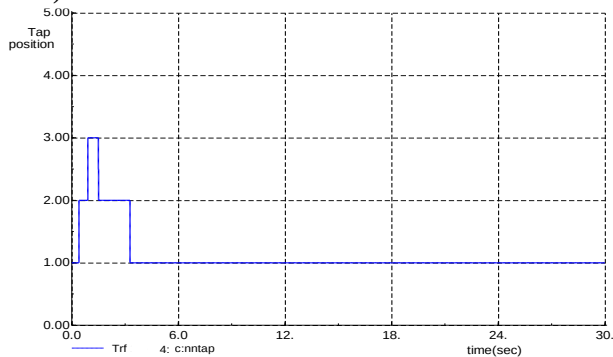


Fig. 17. Tap changer ULTC changes (Trf4)

II) Generators' rotor angle

At $t=0.1$ sec, the buses' voltage drops first and the rotor angle of the generators increases; then, the rotor angle of the generators dampens and converges while oscillating, indicating that the system is stable (Fig. 18).

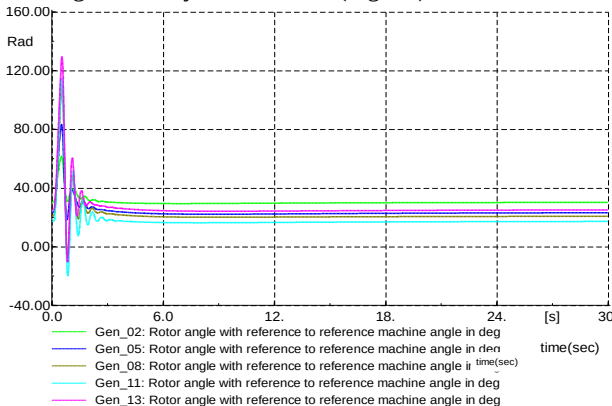


Fig. 18. Rotor angle of generators, with a controller

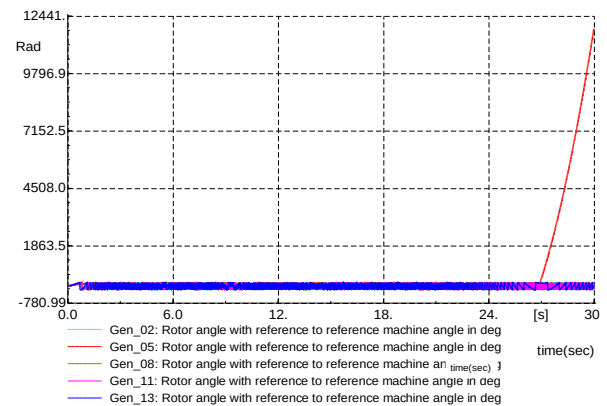


Fig. 19. Rotor angle of generators, without a controller

III) The eigenvalues of a system

Considering the rotor angle of the generators as state variables, after calculations, 36 eigenvalues are obtained. The eigenvalues of the system having a negative true root indicate the stability of the system at a steady-state, shown in APPENDIX A, Second Case Study.

Eigenvalues: $P_i(S) = 0$ and $i=1,2,3,\dots,12$

IV) The stability theory of the switched linear systems

As with paragraph IV of the controller, Section B, according to prerequisite 1 in [26], and given that the duration of system operation in the stable mode is higher, it can be conservatively concluded that the entire system is stable.

B. Simulation results and examining voltage control under disturbance caused by a sudden increase in load from the Sm (L,T,C) scenario

The conditions of the presence of the capacitor in the system and the changes of the transformer tap (Tr4) to voltage control are the same as in Section A for the Sm (F, T, C) scenario.

After simulating at $t=30$ sec, at 0.1 sec, the active power of load 30 increases by 50% while the reactive power of load 30 suddenly increases by 10%, and load 02 increases by 30% while the reactive power of load 02 suddenly rises by 10%; this puts the capacitor bank into the circuit for reactive power compensation.

When the load suddenly increases, the buses' voltage first drops, and the tap changer shifts to status 3; after putting the capacitor bank into the circuit, the buses' voltage improves (reaches >0.95 p.u.) and the tap changer returns to status 1. As in Section A, system stability is measured by four approaches.

I) Buses' Voltage

After performing load distribution calculations, the buses' voltage somewhat drops in the Sm(L,T,C) scenario due to disturbances; it is possible to address the problem using reactive power control equipment.

At $t=0.1$ sec, load 30 suddenly increases by 50%, and load 02 rises by 30%, the buses' voltage drops first and, at $t=0.1$

sec, the capacitor bank enters the circuit; this improves the buses' voltage (Fig. 20).

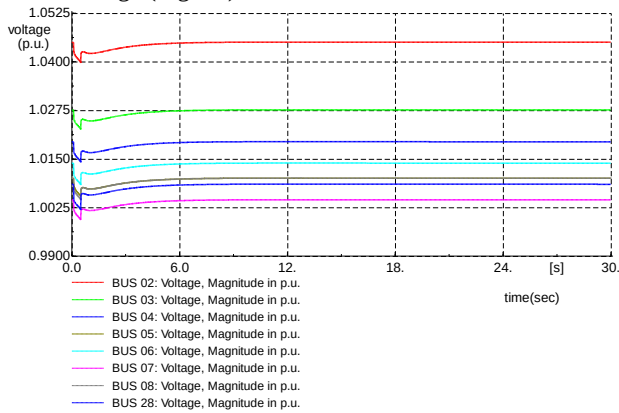


Fig. 20. Voltage of Bus 2 to Bus 8 and Bus 28 of the system, with a controller

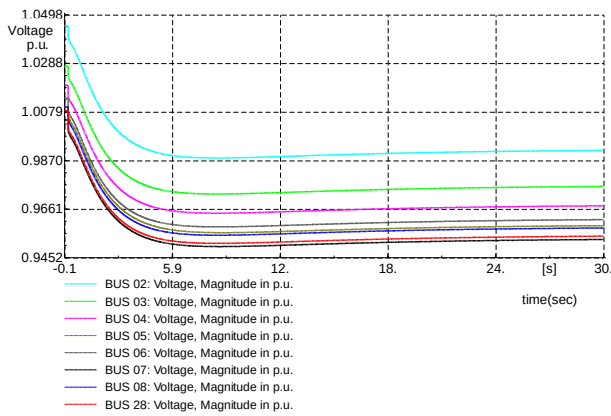


Fig. 21. Voltage of Bus 2 to Bus 8 and Bus 28 of the system, without a controller

As the buses' voltage drops, the tap changer shifts from status 1 to status 2. As the bus voltage improves while the capacitor is present, the tap changer returns to status 1. Fig. 22

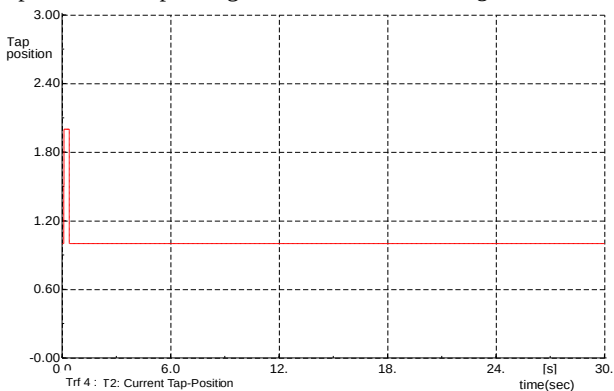


Fig. 22. tap changer ULTC changes(Trf4)

II) Generators' rotor angle

At $t=0.1$ sec, the buses' voltage drops first and the rotor angle of the generators decreases; then, the rotor angle of the generators reaches a constant value and the system becomes stable.

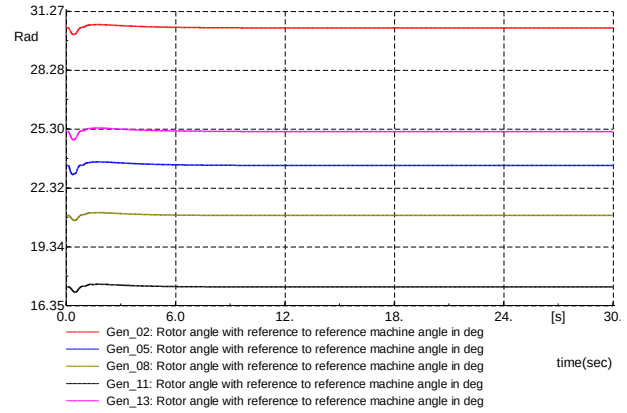


Fig. 23. Rotor angle of generators, with a controller

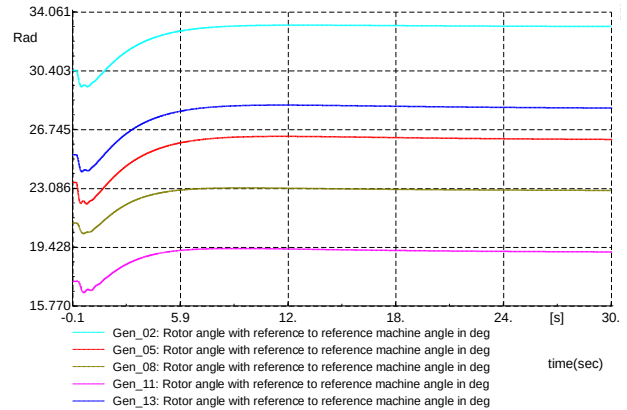


Fig. 24. Rotor angle of generators, without a controller

III) The eigenvalues of a system

Considering the rotor angle of the generators as state variables, after calculations, 36 eigenvalues are obtained. The eigenvalues of the system having a negative true root indicate the stability of the system at a steady-state, presented in APPENDIX A, Second Case Study.

Eigenvalues: $P_i(s) = 0$ and $i=1,2,3,...,12$

IV) The stability theory of the switched linear systems

As with paragraph IV of the controller, Section B, according to prerequisite 1 in [26], and given that the duration of system operation in the stable mode is higher, it can be conservatively concluded that the entire system is stable.

VII. CONCLUSIONS

Herein, the power system was modeled with a new strategy. Discrete states were a combination of discrete events, including changes in the ULTC tap changer with three states, i.e. the presence and absence of a capacitor bank, presence and absence of disturbances resulting from a fault, and a sudden increase in load. In each case of disturbance, the overall behavior of the system was examined in 12 modes, each with specific continuous dynamics. The power system was then modeled as a hybrid automaton, and a closed-loop system was controlled using the ULTC tap changer and capacitor bank. Voltage control and stability were measured

by four approaches of “buses’ voltage”, “generators’ rotor angle”, “the eigenvalues of a system”, and “the stability theory of the switched linear systems”.

The results revealed that the supervisory controller performs well on the control targets, directs the buses’ voltage to the permissible range, and is resistant to changing parameters and applying disturbances, i.e. The system is stable in the transient and steady-state. This method applies to other power systems as well.

APPENDIX A

First Case Study: For example, to obtain A_1 matrix by using the eigenvalues of this system, $P_1(S)$ will be calculated as Equ. (10).

$$P_1(S) = (s+54.5824)(s+36.6425)(s+0.9081-13.7997i)(s+0.9081+13.7997i)(s+0.0776-9.2090i)(s+0.0776+9.2090i)(s+15.1974)(s+11.5742)(s+12.9647)(s+13.2056)(s+3.8289)(s+2.8220)(s+0.2284)(s+0.1565)(s+0.1121-0.0351i)(s+0.1121+0.0351i) \quad (10)$$

After simplifying the coefficients of $P_1(S)$, they will be shown in Equ. (11) as follows.

$$P_1(S) = S^{17} + a_{16}S^{16} + \dots + a_1S + a_0 \quad (11)$$

The coefficients related to $P_1(S)$ in Equ. (11) including

$a_1, a_2, \dots, a_{16}$ will be calculated as presented in Equ. (12).

$$A = \begin{bmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 52 \times 10^{-9} & 1.45 \times 10^{-8} & 1.57 \times 10^{-8} & 7.88 \times 10^{-9} & 1.748 \times 10^{-8} & 4.64 \times 10^{-9} & 1.008 \times 10^{-8} & -1.57 \times 10^{-9} & 1.50 \times 10^{-9} & 1.81 \times 10^{-9} & 1.33 \times 10^{-9} & 7.65 \times 10^{-9} & 3.29 \times 10^{-9} & 9.51 \times 10^{-9} & -1.29 \times 10^{-9} & 153.39 \end{bmatrix} \quad (12)$$

Therefore, it is possible to calculate the matrixes of $A_{17 \times 17}$ for the other 11 states, which means $A_2, A_3, \dots, A_{12}$.

TABLE XI
The Data of WSCC 9-bus system

Bus Number	Load (MW)	Load (MVar)	Generati on (MW)	Generati on (MVar)	Voltage Rated (KV)
1	0	0	0	0	16.5
2	0	0	163	0	18
3	0	0	85	0	13.8
4	0	0	0	0	230
5	125	50	0	0	230
6	90	30	0	0	230
7	0	0	0	0	230
8	100	35	0	0	230
9	0	0	0	0	230

Second Case Study: For example, to obtain A_1 matrix by using the eigenvalues of this system, $P_1(S)$ will be calculated as Equ. (13).

$$P_1(S) = (s+49.6660)(s+49.0020)(s+46.2050)(s+44.8300)(s+42.982)(s+33.6960)(s+27.7090)(s+26.9620)(s+25.1130)(s+26.2520)(s+26.0230)(s+21.0290)(s+2.9040-17.2170i)(s+2.9040+17.2170i)(s+2.2750-15.4000i)(s+2.2750+15.4000i)(s+2.9730-14.7630i)(s+2.9730+14.7630i)(s+2.1960-13.3710i)(s+2.1960+13.3710i)(s+2.5440-13.9090i)(s+2.5440+13.9090i)(s+4.6800)(s+6.0610)(s+5.2570)(s+5.5200)(s+5.8360)(s+2.2940)(s+0.1070)(s+0.5870)(s+0.4750)(s+0.4600)(s+0.3590-0.0060i)(s+0.3590+0.0060i)(s+0.3210) \quad (13)$$

After simplifying the coefficients of $P_1(S)$, they will be shown in Equ. (14) as follows.

$$P_1(S) = S^{36} + a_{35}S^{35} + \dots + a_1S + a_0 \quad (14)$$

The coefficients related to $P_1(S)$ in Equ. (14) including

$a_1, a_2, \dots, a_{35}$ will be calculated as presented in Equ. (15).

$$A_1 = \begin{bmatrix} 0 & 1 & 0 & \dots & 0 \\ 0 & 0 & 1 & \dots & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots \\ 0 & 0 & 0 & \dots & 1 \\ -a_0 & -a_1 & -a_2 & \dots & -a_{35} \end{bmatrix} \quad (15)$$

Therefore, it is possible to calculate the matrixes of $A_{136 \times 36}$ for the other 11 states, which means $A_2, A_3, \dots, A_{12}$.

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