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Power System Dynamic Stability Improvement with UPFC using LQR Technique

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***Abstract*: Many damping controller devices based on other techniques have been proposed time to time. For the study of the damping performance, it has been proposed a power systems model with 'UPFC' and power oscillation damping controller in the present article. The proposed controller performance has been studied under different simulation condition results and that also includes various loading condition, i.e., normal with 100 percent, under loading 80 percent and overloading with 120 percent at different operational points. Finally, a better result has been observed by using the proposed damping controlling device than earlier available existing devices. However, the result obtained by using Eigen value analysis is supported by the facts obtained by the settling time analysis and the analysis of simulation results.**

Keywords: Modeling, Linear quadratic regulator, Small signal stability, Power oscillation damping controller, UPFC

I. INTRODUCTION

Power plays an important role for the economic growth of any country. Model of power system that comprises the generator, transmission lines and different types of loads, is a complex network. With the increase in power demand, there is a need to increase the estimated load on the transmission lines. To fulfill this demand, there are two possible solutions: (i) to install the new power generation and transmission systems and (ii) to improve and modify the existing power system and networks. The main drawback of the existing power system is deteriorating voltage profile with decreasing system stability and security. However, the main reason for these shortcomings is the overload on the transmission lines of the power system. This overall scenario forces us to review ancient transmission methods and various practices adopted.

The newer concepts and aspects must be used without any disturbance in dynamic stability, security of the existing generation systems and transmission lines. [1]. The important parameters that responsible for the determination of the transmitted electrical power are the receiving and sending ends voltages, the line impedance, and phase angle between the voltages. Therefore, both active as well as reactive flow of power may be controlled by controlling either one or more than one parameter. The system to regain or return in its normal operating state by following a small disturbance is the ability of the small-signal stability. Investigations involving the concept of this stability generally comprise the analysis of the linearised state space equations, which can define as the power system dynamics. Previous study reveals that power system stabilizer (PSS) installation is an economical and effective method to reduce low power oscillation frequency and increase system oscillation stability[2]. The recently introduced FACTS (Flexible AC Transmission System) based stabilizer offers another possible way to damp-out oscillations of the power systems. The primary functional works of the FACTS controller is not only its damping duty, but also to increase the overall power system oscillation damping characteristics[3]. Various dynamic models of UPFC [6, 9-12] have already been proposed by different scientist and researcher. Based on linearised "Phillips-Heffron" model, a modified power system model that is installed with UPFC was proposed by Wang [6, 11-12]. This paper proposes the design of the UPFC based POD controller using LQR (Linear quadratic regulator) technique to damp the low frequency electromechanical oscillations and improve the dynamic stability for a wide range of operating conditions [4-5, 13-14]. The procedure to achieve the paper objectives are as follows:

- The model based on SMIB, i.e. single machine infinite bus, also famous as Phillips-Heffron model, is useful because it is installed and equipped with UPFC that uses non-linear equations at the normal application point.[6]
- To adopt the efficient approach for constructing the UPFC controller which can be based on POD i.e. Power oscillation damping.
- To design a POD controller using the LQR technique which placed the eigenvalues according to the mode of oscillation at desired location for which eigenvalues get placed within a 'vertical' degree of stability.
- To demonstrate the effectiveness of the designed POD controller under different controlling parameter.

II. INVESTIGATED SYSTEM

Fig.01 depicts a 'SMIB' power system installed with 'UPFC' between the bus A and B on the transmission line. It consists of the components: (i) Excitation transformer (E_T) (ii) Boosting transformer (B_T) (iii) Two three-phase gate turn off based voltage source converters (VSC's) (iv)Direct current linked capacitor and based on pulse width modulation converters (assumed).

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Moreover, the system parameter details are given in Appendix-A.

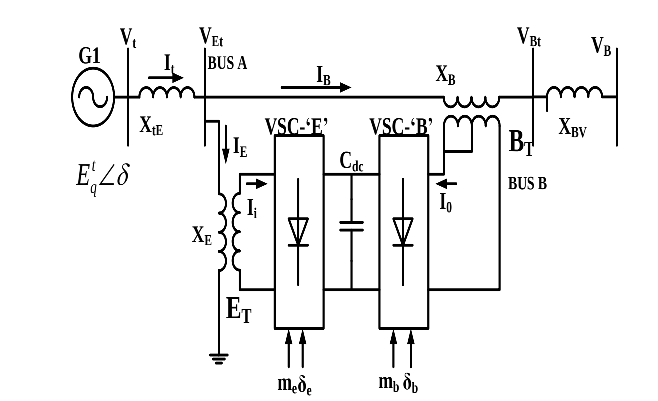

Fig. 01: UPFC installed with SMIB power system.

A. Unified Power Flow Control (UPFC)

The dc link gives bi-directional way to ex-change a real power among the converters attached with a 'SSC' and 'SSSC'. m_e, m_b, δ_e, and δ_b are the UPFC input control parameters, i.e., (i) m_e is the amplitude modulation ratio (AMR) of shunt VSC-'E' (ii) δ_e is the phase angle (PA) of shunt VSC-'E' (iii) m_b is defined as AMR of series VSC-'B' and, (iv) δ_b represents the PA of series VSC-'B' [5]. According to Pandey and Singh [15], the phase angle control method is more efficient than Amplitude modulation control methods and the fact has also been verified on the basis of the results obtained with settling time in the present work (Fig. 2, Fig. 3, Table I). The power system consists of a synchronous generator, which is linked to an infinite bus via a transmission line (TL) and step-up transformer. The generator is expected to have The generator is expected to have AVR that control its terminal voltages. In the present study, The UPFC has been used to analyse the purpose of power system stability and its characteristics. However, the UPFC can fulfil the multiple control objectives.

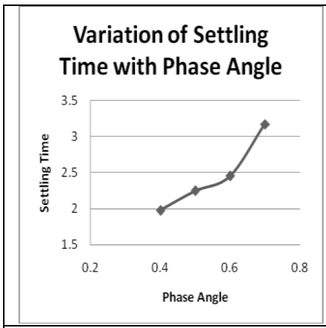

Fig. 2: Variation of Settling Time with Phase Angle

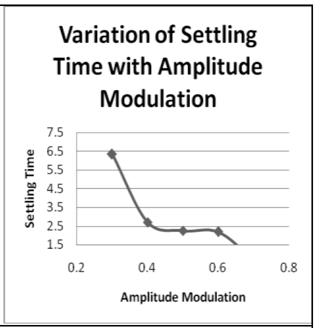

Fig. 3: Variation of Settling Time with Amplitude Modulation

B. Improved version of 'Phillips-Heffron' model for a 'SMIB' System with 'UPFC'

Fig.4 depicts the modified model of Phillips-Heffron fixed with 'UPFC' [6]. It is the modification of the basic model of Phillips-Heffron including UPFC. The present model has been developed by linearising the non-linear model around the nominal operating point. The different parameters of this model are dependent on the system parameters along with the operating condition. In this model: (i) $[\Delta u]$ - The column vector (ii) $[W_{pu}]$, $[W_{qu}]$, $[W_{vu}]$ and $[W_{cu}]$ are the respective row vectors.

Where,

$[\Delta u] = [\Delta m_e\ \ \Delta\delta_e\ \ \Delta m_b\ \ \Delta\delta_b]^T$ $[W_{pu}] = [W_{pe}\ W_{pde}\ W_{pb}\ W_{pdb}]$ $[W_{qu}] = [W_{qe}\ W_{qde}\ W_{qb}\ W_{qdb}]$, $[W_{vu}] = [W_{ve}\ W_{vde}\ W_{vb}\ W_{vdb}]$ $[W_{cu}] = [W_{ce}\ W_{cde}\ W_{cb}\ W_{cdb}]$. The UPFC consist the two main control parameters: m_e is known as the AMR (amplitude modulation ratio) of shunt and m_b is the AMR of series converters. With series AMR controlling the voltage (V) at a bus where 'UPFC' is being installed, which is controlled by reactive power compensation. The value of the series injected voltage can be controlled by variation of parameter of m_b. δ_e regulates the dc voltage at dc link and δ_b controls the results in the real power exchange [14].

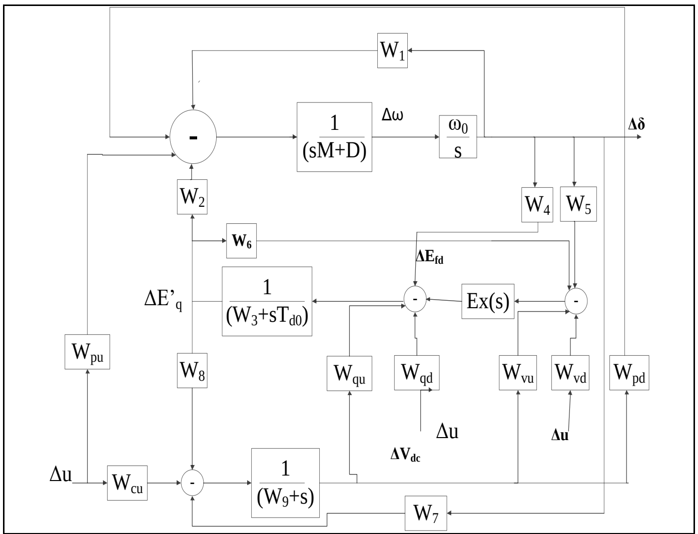

Fig. 4: Improved version of PhillipsHeffron model for a 'SMIB' system with 'UPFC'

C. Model Analysis

$W_1 = 0.1372$	$W_{pb} = 0.0715$	$W_{pde} = -0.2514$
$W_2 = 0.4350$	$W_{qb} = -0.0223$	$W_{qde} = -0.2243$
$W_3 = 0.4727$	$W_{vb} = 0.0145$	$W_{vde} = 0.0782$
$W_4 = 0.0598$	$W_{pe} = 0.7860$	$W_{cb} = 0.1763$
$W_5 = -0.0159$	$W_{qe} = -0.2451$	$W_{ce} = 0.0018$
$W_6 = 0.5092$	$W_{ve} = 0.1597$	$W_{cdb} = 37.7306$
$W_7 = 80.9318$	$W_{pdb} = -0.0229$	$W_{cde} = 77.2952$
$W_8 = 21.0677$	$W_{qdb} = -0.0204$	$W_{pd} = 0.4287$
$W_9 = 40.6634$	$W_{vdb} = 0.0061$	$W_{qd} = -0.1337$
$W_{vd} = 0.0871$		

D. Design of POD Controller (Linear Quadratic Regulator Technique)

By using the Phillip-Heffrons model, the linearised state-space model for 'SMIB' power system is expressed:

$$\dot{X} = AX + BU \qquad (1)$$

In the equation (1):

The terms A and B are the matrices of the system

X: The system state vector

U: The input state vector

Within the assumption of system linearity, the matrices 'A' and 'B' behave as constant. The matrix 'K' of the 'LQR' vector is determined by setting the value u(t)= -K.x(t). In the sequence to find the PI (performance index) [7],[8] the following equation (2) is considered:

$$J = \int_0^\infty \left(x^T Q x + u^T R u \right) dt \qquad (2)$$

In the given equation (2) the term $u^T Ru$ accounts for the expenditure of the energy on the control efforts. The matrix [Q] and [R] gives the relative importance of the error and the expenditure of this energy.

The equation (2) can further be written as

$$J = \int_0^\infty \left(x^T Q x + x^T K^T R K x \right) dt = \int_0^\infty x^T (Q + K^T K R) x dt \qquad (3)$$

For solving the parameter-optimization problem, set the equation as

$$x^T (Q + K^T R K) x = -\frac{d}{dt}(x^T P x) \qquad (4)$$

$$\left. \begin{aligned} x^T (Q + K^T R K) x &= -\dot{x}^T P x - x^T P \dot{x} \\ &= -x^T [(A - BK)^T P + P(A - BK)] x \end{aligned} \right\} \qquad (5)$$

By comparing both the sides of the above equation (5), the equation (5) must held correct for any x,

$$(A - BK)^T P + P(A - BK) = -(Q + K^T R K) \qquad (6)$$

In the aforementioned equation (6), R is a positive definite Hermitian or real symmetric matrix (assume), so it can be written as ($R=T^T T$), where T is taken as nonsingular matrix, and

$$A^T P + PA + [TK - (T^T)^{-1} B^T P] - PBR^{-1} B^T P + Q = 0 \qquad (7)$$

For the minimization of J w.r.t. K, need to minimize the following term,

$$x^T [TK - (T^T)^{-1} B^T P]^T [TK - (T^T)^{-1} B^T P] x \qquad (8)$$

Equation (8) has nonnegative value, however, the minimum occurs when it has value of zero, or when

$$TK = (T^T)^{-1} B^T P \qquad (9)$$

$$K = T^{-1} (T^T)^{-1} B^T P = R^{-1} B^T P \qquad (10)$$

Thus, a control law is

$$u(t) = -Kx(t) = -R^{-1} B^T P x(t) \qquad (11)$$

Here, matrix (P) must be satisfy the reduced 'Riccati equation'

$$A^T P + PA - PBR^{-1} B^T P + Q = 0 \qquad (12)$$

Steps for controller design

- Required data – A, B, Q, R and N matrix
- Data for calculation- K matrix, P matrix and eigenvalue
- Set the N matrix value as zero
- The positive definite 'real symmetry matrix' are 'Q' and 'R'.
- Calculation of the P matrix
- Estimate the value of K matrix

III. SIMULATION RESULTS UNDER DIFFERENT SYSTEMS AND AT VARIOUS LOADING CONDITIONS

The proposed model has been used to study the damping performance of 'UPFC' in 'SMIB' power system (Figure 1). To study the performance of the proposed controller, the simulation results have been analyzed using various operating and loading conditions as well. For an example, at normal operating point, the corresponding line loading of 1.00 pu and also at 20 percentage decrease as well as increase in line loading are shown. By analyzing the results, it is clearly noticed that the proposed controller deliver the better performance in reduction ofof overshoot and also the settling time in comparison to the system using no UPFC or the system using UPFC only. Those simulation results are considered only, in which there is variation in system- state and rotor angle (δ) of the generator.

Table I: Settling Time and Overshoot Analysis

Time/ Overshoot → Damping constant (D) ↓	System	Settling Time	Overshoot
D = 0.0	System without UPFC	1.5987	23.3572
	System with 'UPFC' only	4.8945	3.9219
	System with 'POD' ' UPFC' Controller	0.8477	2.4629
D = 4.0	System without 'UPFC'	14.5883	3.7625
	System with 'UPFC' only	3.5833	3.7138
	System with 'POD UPFC' Controller	0.9153	2.4603
D = 8.0	System without 'UPFC'	6.6347	3.5870
	System with 'UPFC' only	2.6667	3.4349
	System with 'POD UPFC' Controller	0.8874	2.4533
Settling Time and Overshoot for weak stable 'SMIB' system. (pf=0.85, me =0.5, δe =0.5, mb =0.5, δb =0.5)			

IV. SIMULATION RESULT (WAVEFORM) ANALYSIS

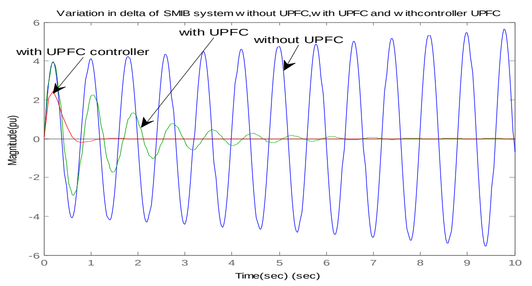

Fig.5: Delta variation with 'UPFC', without 'UPFC' and with 'POD' controller of unstable (D=0.0) system with nominal loading (1.00 pu).

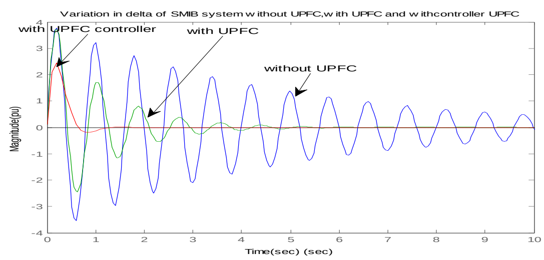

Fig.6: Delta variation with 'UPFC', without 'UPFC' and with ' POD' controller of weak (D=4.0) system with nominal loading (1.00 pu)

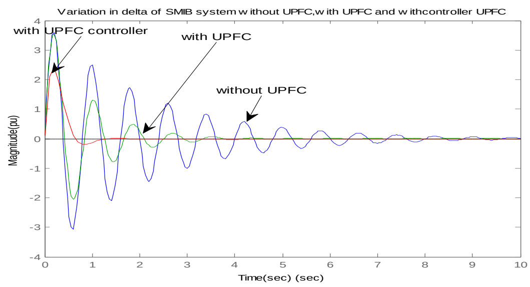

Fig.7: Delta Variation without and with 'UPFC', and with 'POD' controller of strong (D=8.0) system with nominal loading (1.00 pu).

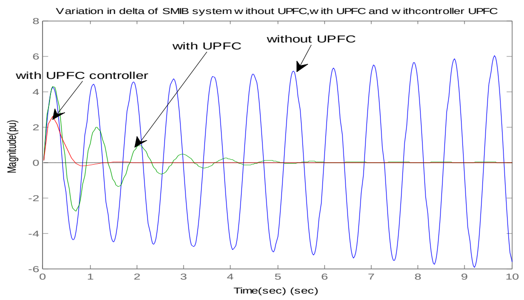

Fig.8: Delta Variation without and with 'UPFC', and with 'POD' controller of weak (D=0.0) system with nominal loading (0.80 pu)

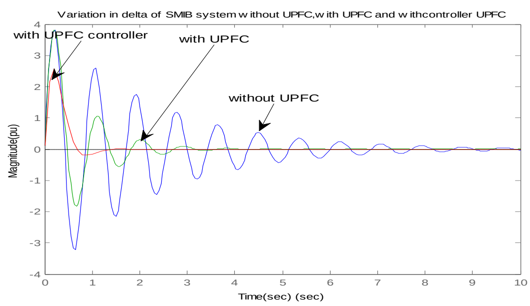

Fig.9: Delta Variation without and with 'UPFC', and with 'POD' controller of strong (D=8.0) system with nominal loading (0.80 pu).

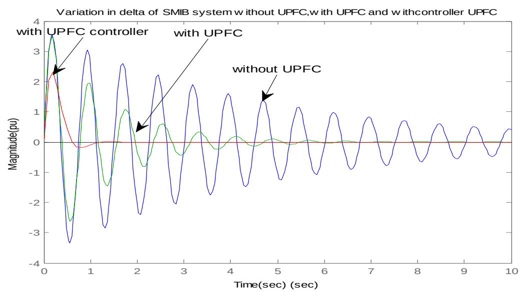

Fig.10: Delta Variation without and with 'UPFC', and with 'POD' controller of weak (D=4.0) system with nominal loading (1.20 pu)

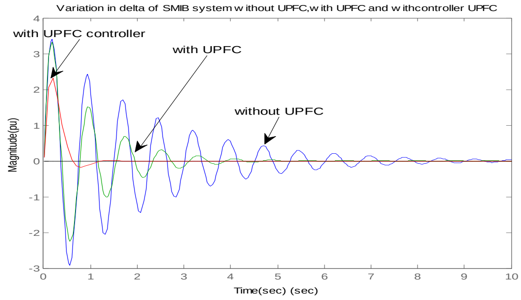

Fig.11: Delta Variation without and with 'UPFC', and with 'POD' controller of strong (D=8.0) system with nominal loading (1.20 pu)

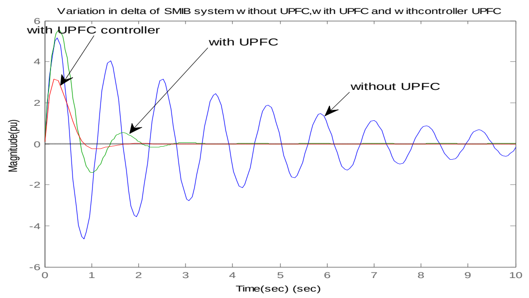

Fig.12: Delta Variation without and with 'UPFC', and with 'POD' controller of weak (D=4.0) system without loading.

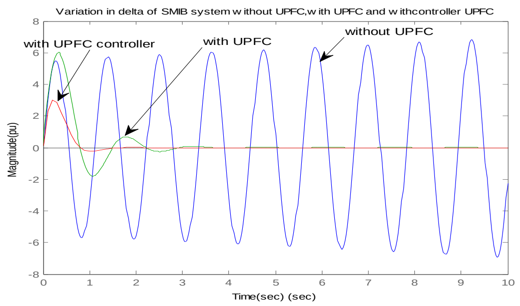

Fig.13: Delta Variation without and with 'UPFC', and with 'POD' controller for same modulation index (0.60)

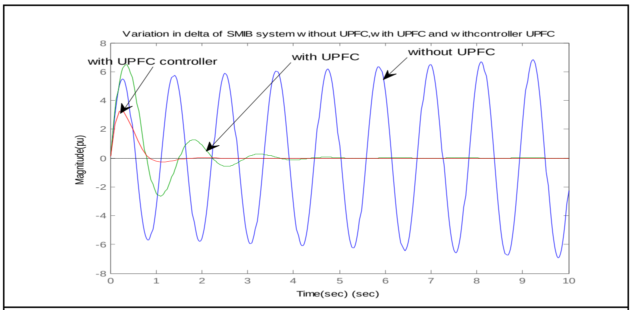

Fig.14: Delta Variation without and with 'UPFC', and with 'POD' controller for same phase angle (0.60)

V. EIGEN VALUES ANALYSIS

Table II: Eigen values Analysis

Controller → Damping constant (D) ↓	System without 'UPFC'	System with the 'UPFC' only	System considered with the 'POD UPFC' controller
	-98.7309	-102.18	-102.18
	0.0224 + 5.6180i	-33.02	-33.02
D = 0.0	**0.0224 - 5.6180i**	**-1.26 + 4.63i**	**-3.79 + 4.63i**
	-1.6663	**-1.26 – 4.63i**	**-3.79 – 4.63i**
	0	-3.35	-3.35
	-98.7309	-102.18	-102.18
	-0.2270 +5.6116i	-33.04	-33.04
D = 4.0	**-0.2270 - 5.6116i**	**-1.62 + 4.70i**	**-4.86 + 4.70i**
	-1.6674	**-1.62 – 4.70i**	**-4.86 – 4.70i**
	0	-3.12	-3.12
	-98.7309	-102.18	-10218
	-0.4765 + .5939i	-33.05	-33.05
	-0.4765 - 5.5939i	**-1.98 + 4.78i**	**-5.95 + 4.78i**
D = 8.0	-1.6686	**-1.98 – 4.78i**	**-5.95 – 4.78i**
	0	-0.0289	-2.89

Eigen values for weak stable 'SMIB' system. (pf=.85, m_e =0.5, δ_e =0.5, m_b =0.5, δ_b =0.5*)*

VI. RESULT AND DISCUSSION

In this paper, the authors have tried to study and elucidate the effect of various operating conditions, viz (i) System using controller UPFC (LQR Technique), (ii) System using neither UPFC nor controller UPFC (iii) System using UPFC only, on the performance of system. The simulation results (figure 5 to 14) and eigen value analysis (Table II) support the system model with controller UPFC using the LQR technique for the dynamic stability enhancement. Settling time analysis (Table I) also supports the Facts. A system with UPFC controller is capable to maximize the damping control torque and minimize the settling time, and hence improve the system stability.

VII. CONCLUSION

The power system having low frequency electromechanical oscillation was damped via LQR technique-based POD controller which when is applied independently with UPFC and was investigated for a SMIB power system. To maximize the system damping ratio among all the complex eigenvalues and the minimize the associated design problems of controller, an eigenvalue-based objective function has been developed.

Efficiency of the designed damping controller have been checked based on eigen value analysis (Table II), settling time (Table I), overshoot and simulation result analysis (Figure 5 to 14) for different systems and at different line loading conditions. During the systematic analysis of the present study, It has been observed that the designed damping controlling device provides the effective outcomes for controlling the damping of the system.

Although, based on other techniques, some similar damping controller devices have been projected earlier, but the proposed damping controlling device is giving comparative better result than the earlier existing devices, meanwhile, the fact is also supported by the results obtained by using eigen value analysis, settling time and simulation results.

APPENDIX-A

System Data-

Generator data:

M = 8.00 M J/ MVA; X_d = 1.001; X'_d = 0.3001; T_{d0} = 5.05 second;

X_q = 00.600; δ = 00.698, and radian; E'_q =1.00

Excitation System data:

K_a= 10.00; T_a = 00.010 sec.

Transformers data:

X_b = 00.030; X_e = 00.030

Transmission line data:

X_{BV} = 00.30; X_{tE} = 00.30

Operating conditions:

V_b= 1.00; pf = 00.850; Frequency = 50.00 Hz.

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