Performance Analysis and Improvement of a Power System Network Using a Unified Power Flow Controller

Dr. S. Krishnamurthy and G.F. Noudjiep Djiepkop

Abstract—Rural electrification is achieved by increasing the power generation while minimizing the transmission losses. Alternative ways of improving the capability of the transmission line power flows is by using the newly developed power electronics controllers and integrating them into the power system networks. Unified Power Flow Controller (UPFC) is one of the latest technologies of the Flexible AC Transmission Systems (FACTS). It is used to compensate reactive power, control the power flow and to enhance the stability of the transmission system. This paper proposes an approach of integrating the UPFC-based FACTS power electronics controller into the transmission system in order to use it for estimation of the performance of the power system transmission network. Then the UPFC is used to resolve the load flow problem and provide voltage regulation in the power system network. The performance of the power system network with/without UPFC is investigated in this paper and the simulation results are presented.

***Index Terms*—Flexible AC Transmission Systems, Power systems, Reactive Power Compensation, Unified Power Flow Controller, Voltage Regulation**

1 INTRODUCTION

The rapid growth of the consumers energy need causes existing plants to be overloaded. Due to economic and geographical concerns, the construction of new power plants and transmission lines has been proven to be a big challenge [2]. Therefore the research investigation on optimisation methods used for power flow problem has been a big focus due to the eminent decrease of traditional sources of energy (charcoal, Oil, natural gas) and the desire on policies to reduce the carbon emission produced by the power plants. Transmission lines with power flow exceeding their limit cause the power system to deteriorate. Therefore, there is a need to increase the flexibility and the performance of the existing transmission systems [1]. Flexible Alternative Current Transmission Systems (FACTS) are used for this purpose.

The technology development introduced a new FACTs device to the power utility called Unified Power Flow Controller (UPFC) for the reactive power compensation [3] and [7]. The basic circuit arrangement of the device and the mode of control of the real and reactive power were described in [7]. The UPFC could offer voltage regulation, series/shunt compensation, phase angle regulation and the ability to control the real and reactive power at both ends of the transmission lines independently. In addition to that a comparison study between the UPFC, the Thyristor Controlled Series Compensation (TCSC) and the Thyristor Controlled phase angle Regulator is investigated in [7] and the superior capability of the UPFC was demonstrated. The study on the effect of power flow and transmission losses on a large scale power system is investigated in [8]. The selection of the best position for placement of the UPFC on the long transmission line is described in [8]. The study recommended that the shunt connected UPFC module is best to control the reactive power produced by the generator and the voltage at the bus where the UPFC is connected and it has no control over the real power flow in the transmission lines [8], whereas series connected UPFC module can control both the real and the reactive power in the transmission lines. On basis of the above research investigation, this paper used UPFC device for the reactive power compensation, since it offers extended functionality compared to the other FACTS technologies and it is used to enhance the power flow transfer capability.

This paper is organized as follows: Introduction in section 1, description of the power system network and its input data are given in section 2. Section 3 presents the performance analysis of the load flow problem. In section 4, the performance of the power system network is improved by using an UPFC. The UPFC's basic operating principle and its topology are described in this paper.

2 DESCRIPTION OF THE CASE STUDY

The single line diagram of the 3-bus power system network used as a case study and is given in Figure 1. It consists of 2 generators, 3-buses and a load. The buses are interconnected through transmission lines as shown in Figure 1. The bus type, the initial bus voltage magnitude and phase angle, as well as the real and reactive power at the generators and the load are given in Table 1. The input data of the power transmission lines and its Geometric Mean Radius (GMR) are given in Table 2 [5].

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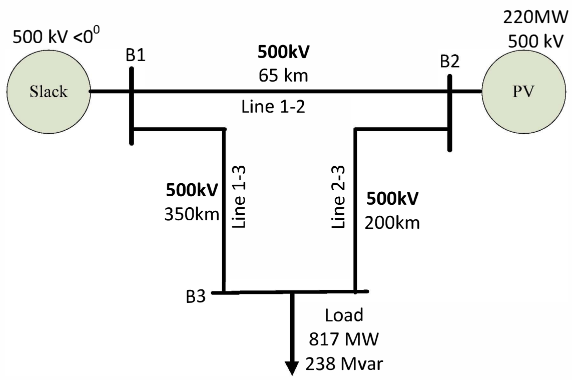

Fig. 1. Single line diagram of the considered three-bus power system network

Table I. Bus data of the three-bus power system

Bus NO.	Bus Type	Voltage in per unit	δ in degrees	Grid powers		Load Power	
				P_G (pu)	Q_G (pu)	P_L (pu)	Q_L (pu)
1	Swing	1.0	0	-	-	0	0
2	PV	1.0	-	2.2	-	0	0
3	Load	-	-	0	0	8.16	2.38

The line voltage is 500kV and the base power is assumed to be 100MVA.

Table II. Transmission line data of the three-bus power system

Line		Conductor type	I rating (A)	GMR (cm)	Resistance at 60Hz (Ω)	Right of Way (km)
From bus	To bus					
1	2	partridge	460	0.6614	0.2393	65
1	3	Finch	1110	1.3259	0.0602	350
2	3	Partridge	460	0.6614	0.2393	200

3 PERFORMANCE ANALYSES OF THE POWER SYSTEM NETWORK WITHOUT UPFC

A load flow study is conducted for the 3-bus power system network and the power system parameters such as voltages, currents, active and reactive powers are determined at the given points of the electric network under normal operating conditions. It is essential to analyse the operation of the existing power system network for system planning and future expansion.

3.1 Problem formulation

The analysis of the load flow requires the transmission line parameters to be known. The resistances of the lines are given and their inductance (L) and capacitance (C) parameters can be calculated using the input data given in Table 2. It is assumed the behaviour of the power system to be symmetrical under the normal conditions. Therefore only positive sequence components are considered in this paper.

The three phase transmission lines are equally spaced and the line inductance is given in (1), [7].

$$L = 2 \times 10^{-7} \cdot ln \frac{D}{GMR} \;\; (H/m) \tag{1}$$

L is the inductance in Henry per meter
D is the spacing between the lines in meters
GMR is the Geometric Mean Radius of the conductor in meters.

The capacitance to neutral of a given line is given in (2), [7]. The effect of the capacitance between the earth and the neutral conductors is neglected.

$$C = \frac{2\pi \times 8.85 \times 10^{-12}}{ln \frac{D}{GMR}} \;\; (F/m) \tag{2}$$

C is the capacitance between the line and the neutral in Farads per meter.
The spacing between the conductors is 10 meters.

Power systems are often represented by the admittance bus which is given in (3), [4]. The admittance is used to simplify the hurdle associated with power flow study. The elements of an admittance bus describe the admittances liaison between the buses of the power system network.

$$Y_{bus} = \begin{bmatrix} Y_{11} & -Y_{12} & \cdots & -Y_{1n} \\ -Y_{21} & Y_{22} & \cdots & -Y_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ -Y_{n1} & -Y_{n2} & \cdots & Y_{nn} \end{bmatrix} \tag{3}$$

n is the number of buses in the power system network
Y_{11}, Y_{22} and Y_{nn} are called self-admittances.

The diagonal elements of the admittances are the sum of all admittances connected to that bus and is denoted by the double subscript. The admittance of the capacitance created by the transmission line should be included. The off-diagonal elements are called mutual admittance and are the negative of the sum of all the admittance directly connected between the buses identified by the double subscripts.

Admittance is the inverse of the impedance. Thus, the line impedance needs to be calculated and it is obtained using (4), [7].

$$Z = (R + j2\pi fL) \cdot l \;\; (\Omega) \tag{4}$$

Z is the impedance of the line in Ohms
R is the resistance in Ohm per meter
L is the inductance of the line in Henry per meter
l is the length of the line in meter

The Gauss-Seidal method is used to solve the power flow problem using (5) and (6) respectively [7].

$$V_i = \frac{1}{Y_{ii}} \cdot \left[\frac{P_i - jQ_i}{V_i^*} - \sum_{k=1}^{n} (Y_{ik} \cdot V_k)\right] \; (k \neq i) \qquad (5)$$

$$P_i - jQ_i = V_i^* \cdot \left[Y_{ii} \cdot V_i + \sum_{k=1}^{n} (Y_{ik} \cdot V_k)\right] \; (k \neq i) \qquad (6)$$

Assuming $V_2 = 1\angle 0°$, $V_3 = 1\angle 0°$ as initial values, the load flow results are given below:

$$V_2 = 1\angle(-2.813°)pu$$

$$V_3 = 0.8745\angle(-15.91°)pu$$

$P_1 = 6.6789\,pu$, $Q_1 = -0.90589\,pu$ and $Q_2 = 159.261\,Mvar$

The power flow in each line is calculated using (7) to (10) respectively [7].

$$P_S = \frac{|A|}{|B|}|V_S|^2 \cos(\beta - \alpha) - \frac{|V_R||V_S|}{|B|}\cos(\beta + \delta) \qquad (7)$$

$$Q_S = \frac{|A|}{|B|}|V_S|^2 \sin(\beta - \alpha) - \frac{|V_R||V_S|}{|B|}\sin(\beta + \delta) \qquad (8)$$

$$P_R = \frac{|V_R||V_S|}{|B|}\cos(\beta - \delta) - \frac{|A|}{|B|}|V_R|^2 cos(\beta - \alpha) \qquad (9)$$

$$Q_R = \frac{|V_R||V_S|}{|B|}\sin(\beta - \delta) - \frac{|A|}{|B|}|V_R|^2 sin(\beta - \alpha) \qquad (10)$$

P_S, Q_S are the real and reactive powers at the sending end line.

P_R, Q_R are the real and reactive powers at the receiving end line.

V_S, V_R are the voltages at the sending and receiving end lines respectively.

δ is the phase angle between the sending and receiving end voltages

$A = |A|\angle\alpha$ and $B = |B|\angle\beta$ are parts of the ABCD parameters for a two bus transmission line. A and B are calculated using (11) and (12) respectively.

$$A = \cosh(\sqrt{Z.Y}) \qquad (11)$$

$$B = \sqrt{\frac{Z}{Y}}.\sinh(\sqrt{Z.Y}) \qquad (12)$$

Y is the total shunt admittance of the given transmission line.

The summary of the hands-on calculation for the line flow results is given in Table III.

Table III. Transmission line flow results of the considered power system network

Line	Sending end		Receiving end	
	P_S (MW)	Q_S (MVar)	P_R (MW)	Q_R (MVar)
1-2	291.39447	-140.7854	285.0685	-108.81
1-3	376.4968	50.1965	361.9282	177.9579
2-3	505.1557	50.451	454.2956	59.2809

3.2 Simulation model of the Power system network

The single line diagram given in Fig. 1 is modelled in MATLAB Simpowersystem environment as given in Fig. 2. The load flow problem is solved using the base of 500kV and 100MVA.

The Gauss-Seidal load flow result for the considered power system is given in Table IV.

Table IV. Load flow results of the power system network without UPFC circuit

Bus No.	Load flow results					
	V (pu)	V phase Angle in degree	Generation		Load	
			Real power in MW	Reactive power in Mvar	Real power in MW	Reactive power in Mvar
B1	1.00	0.00 °	667.72	-90.42	-	-
B2	1.00	-2.81 °	220.00	159.49	-	-
B3	0.87	-15.91°	-	-	816.00	238.00

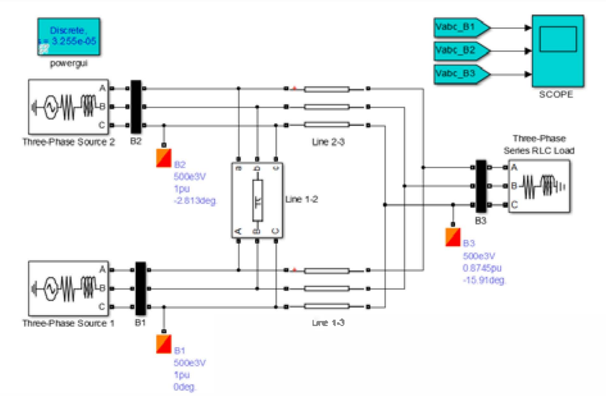

Fig. 2. Power system simulation model without UPFC

3.3 Discussion of the load flow results of the power system network without UPFC

As per the IEEE standard, the nominal voltage rating is 1pu with an allowable tolerance of ±5%. The results obtained from the simulation are corresponding to the calculated one. But the load bus (B3) voltage is dropped to 0.87pu, which is clearly identified as an under-voltage condition.

It is noted that the line 2-3 is a partridge conductor, with a current rating of 460A. Therefore maximum power flow through the line 2-3 can be calculated using (13), [7].

$$P_{max} = \sqrt{3}\, V \cdot I \qquad (13)$$

$$P_{23max} = \sqrt{3} \times 500 \times 10^3 \times 460 = 398.3717$$

But from the load flow results given in Table 3, it can be seen that the transmission line 2-3 carries more than 500MVA. Hence, Line 2-3 is overloaded.

Line 1-3 is a finch conductor with a current carrying capacity of 1110A. The maximum power it can carry is calculated using (13).

$$P_{max2} = \sqrt{3} \cdot 500 \times 10^3 \times 1110 = 961.2882MVA$$

So this power system network could supply loads up to 1359.66MVA.

In the past, this kind of problem would result to the transmission lines to be decommissioned and redesigned. But nowadays, the performance of the power system network can be improved by installing modern FACTS controllers such as UPFC. This method is considered in the paper to improve the power system network performance.

4 IMPROVEMENT OF THE POWER SYSTEM NETWORK USING A UPFC

A UPFC is inserted in the power system network to improve the operation of the existing power system. In this paper, UPFC is used to push more power through the line 1-3 and the limit the power flowing through the transmission line 2-3. The next section of the paper analyses the operation of the power system network with UPFC.

4.1 Basic structure of the UPFC

The Unified Power Flow Controller (UPFC) is a combination of the Static Synchronous Compensator (STATCOM) and the Static synchronous Series Compensator (SSSC) interconnected via a DC link [6]. The single line diagram of the UPFC is shown in Fig. 3.

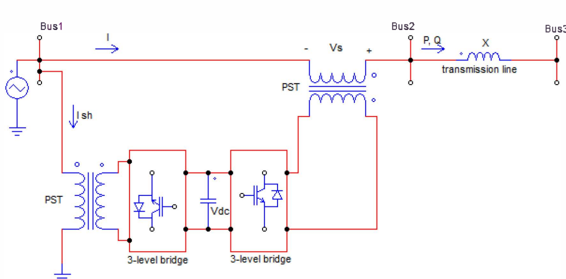

Fig. 3. Single line diagram of the UPFC circuit

By changing the magnitude and the angle of the injected voltage VS, the series compensator can control the real and reactive powers (P and Q) at the bus (B2). The line current flows through the series compensator, resulting in an exchange of real and reactive power between the unified power flow controller and the transmission systems. The shunt controller supplies or absorbs the real power at the DC link and simultaneously generates or absorbs the reactive power, and provides voltage control at the bus (B1) [7].

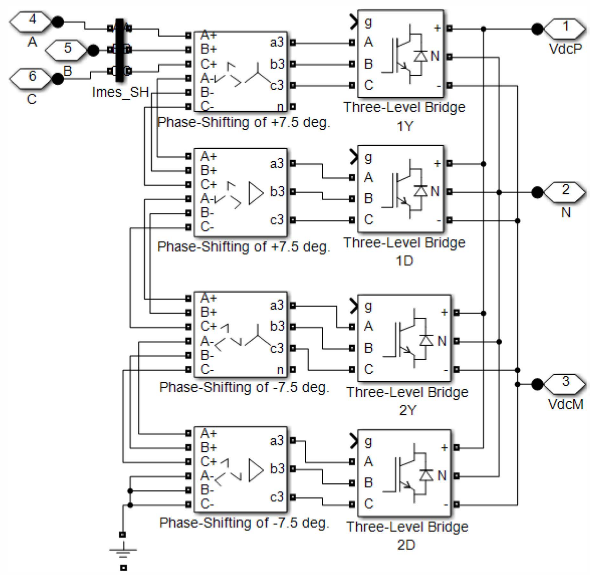

Fig. 4. Configuration of the transformers and the three-level bridge circuit in the Voltage Source Controller

Fig. 5. shows the power system network with the UPFC connected between the buses B1 and B2. The transformers in the UPFC converters are phase shifting (Zig-Zag) transformers and they are connected to 3-level bridges as shown in Figure 4. The 30° phase-shift between the delta and wye secondary windings cancels harmonics of order 5+12n and 7+12n (n = 0, 1, 2, …n). Therefore 15° phase shift between the two 2 upper and 2 lower transformers cancels the harmonics of order 11+24n and 13+24n (n = 0, 1, 2,…n). The 23rd, 25th, 47th and 49th are the first harmonics not cancelled by this configuration of transformers. The 23rd and 25th are attenuated by choosing a firing angle sigma = (1800 - 7.50) = 172.5° for the 3-level inverters. Therefore, the 47th and 49th are the first significant harmonics [8].

4.2 Simulation results of the power system network with UPFC

The voltage at the swing bus and the load bus are obtained as shown in Fig. 6. Additionally, the real and reactive power at the bus (B2) and the voltage injected in the network by the UPFC are obtained as shown in Fig. 7. The UPFC circuit goes ON after 0.25s. The load flow and transmission lines results with UPFC circuit is given in Table V and Table VI respectively.

Table V. Load flow results of the power system network without UPFC circuit

Line	Sending end		Receiving end	
	P_S (MW)	Q_S (MVar)	P_R (MW)	Q_R (MVar)
1-2	222.17	-187.62	217.41	-151.69
1-3	495.71	129.5	472.83	222.58
2-3	457.44	-4.28	417.73	37.15

The simulation results show that the swing bus voltage is maintained at 1 pu and the load bus voltage is improved from 0.87 pu to 0.91pu. Moreover, the real and reactive power at the sending end line 1-3 are maintained constant respectively at 3.76 pu and 0.5 pu for 0.25s. After 0.25s, the UPFC circuit is introduced in the power system network which pushes the real and reactive powers in the network and reaches a steady state at 4.95 pu and 1.26 pu respectively at 0.5s as shown in Fig. 7.

Table VI. Load flow results of the power system network with UPFC circuit

Bus No	Load flow results					
	V (pu)	V phase angle	Generation		Load	
			Real power in MW	Reactive power in Mvar	Real power in MW	Reactive power in Mvar
B1	1.00	-1.75 °	684.93	-102.41	-	-
B2	1.01	-4.15 °	240.02	147.41	-	-
B3	0.91	-15.87 °	-	-	890.56	259.73

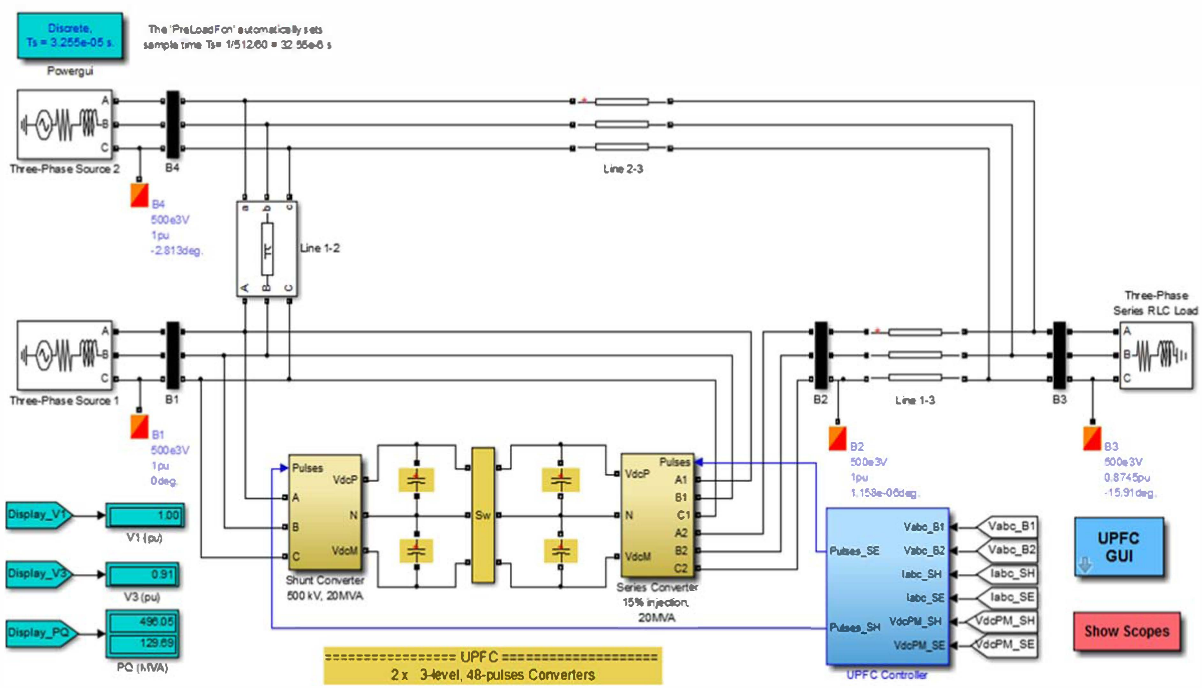

Fig. 5. Power systems network with UPFC

4.3 Simulation results of the power system network with UPFC

The UPFC is introduced in the considered power system network at 0.25 s, then injecting a voltage into the network and increases both real and reactive powers at the bus B2. The voltage injected by the UPFC also provides voltage regulation at the load bus. Therefore load bus voltage rises from 0.87 pu to 0.91 pu.

The power flow in the transmission line 2-3 can be calculated using (7) and (8). It is found that in the power system network with UPFC, the line 2-3 is no longer overloaded. However, the magnitude of the load bus voltage is still below the IEEE standard specification. This can be overcome by providing compensation and it will be considered in future works.

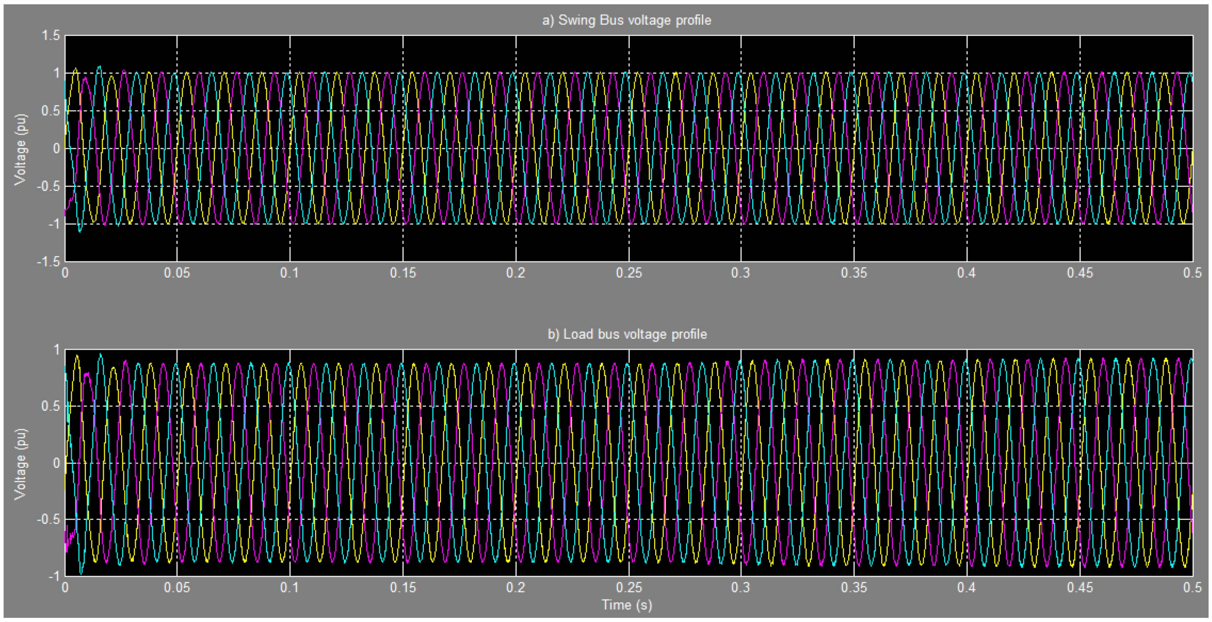

Fig. 6. a) Swing bus voltage profile b) Load bus voltage

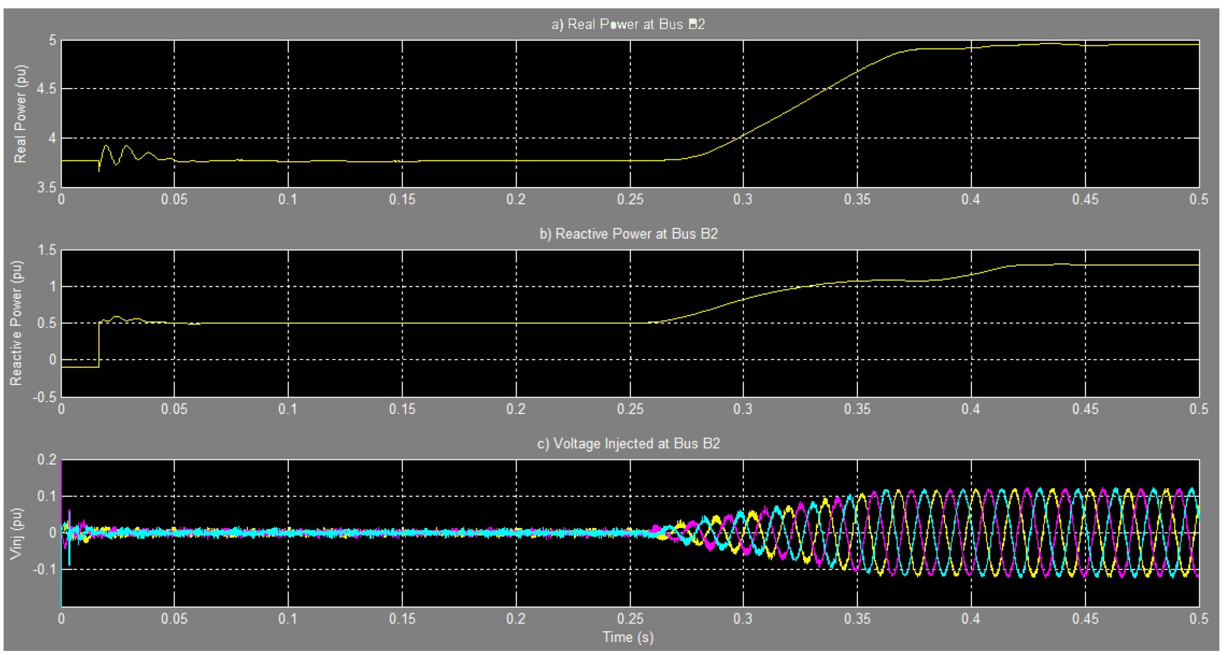

Fig. 7. a) Real power at the bus (B2), b) Reactive power at the bus (B2), c) Voltage injected at the bus (B2)

5 CONCLUSION

This paper presented the performance analysis and improvement of a power system network using a Unified Power Flow Controller. The considered power system network was modelled and analysed with and without the UPFC circuit. In addition to that, the Gauss-Seidal method is used to determine the real and reactive powers at the sending and receiving ends of the lines (without UPFC circuit). It was proved that the hands-on power flow calculation results are close to the MATLAB Simpowersystem results. It is observed that without the UPFC circuit, the transmission line 2-3 was overloaded and the load bus voltage experienced an undervoltage condition. This situation motivated engineers and us to use the modern FACTS device called UPFC in the power system network which is implemented in this paper. The simulation results show that the voltage is regulation is improved and the overload conditions on the existing power system network are avoided by using the UPFC circuit. The simulation results of the power system network show that the performance of the power system network is improved using the UPFC circuit.

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