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Power Flow Analysis based on Newton-Raphson Method for Nine Bus Power System Using PowerWorld Simulator

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Abstract: *In a power system, power flows from generating station to the load through different branches of the network. The flow of active and reactive power is known as load flow or power flow. Power flow analysis is important for Electrical Engineering to understand, but the analysis can often be long and tedious. Hand calculations are suitable for the estimation of the operating characteristics of a few individual circuits, but accurate calculations of power flows or short circuits analysis would be impractical without the use of computer software. One way to either check answers or solve large cases would be to use a software package such as PowerWorld Simulator. This paper presents power flow analysis based on the Newton-Raphson method under steady state conditions to determine the various bus voltages, phase angles, active and reactive power flows through different branches, generators, transformers and loads of Western System Coordinating Council (WSCC) nine bus power system by using the PowerWorld Simulator 20 Education/ Evaluation.*

Key Words: *power flow analysis, PowerWorld simulator, nine bus power system, Newton-Raphson method*

1. INTRODUCTION:

Power flow analysis is the most fundamental study to be performed in a power system both during the planning and operational phases. It constitutes the major portion of electric utility. The study is concerned with the normal steady state operation of power system and involves the determination of bus voltages and power flows for a given network configuration and loading condition. The results of power flow analysis is help to know (1) the present status of the power system, required for continuous monitoring, (2) alternative plans for system expansion to meet the ever increasing demand. Gauss-Seidel method, Newton-Raphson method and Fast Decoupled method are commonly used to get the power flow solution. These Numerical methods are techniques by which mathematical problems are formulated so that they can be solved with arithmetic operations and they usually provide only approximate solution. The effective and most reliable among the three load flow methods is the Newton-Raphson method because it converges fast and is more accurate. Successful power system operation under normal balanced three-phase steady-state conditions requires; (1) generation supplies the demand (load) plus losses, (2) bus voltage magnitudes remain close to rated values, (3) generators operate within specified real and reactive power limits, (4) transmission lines and transformers are not overloaded.

As electric utilities have grown in size and the number of interconnections has increased, planning for future expansion has become increasingly complex. The increasing cost of additions and modifications has made it imperative that utilities consider a range of design options, and perform detailed studies of the effects on the system of each option, based on a number of assumptions: normal and abnormal operating conditions, peak and off-peak loadings, and present and future years of operation. A large volume of network data must also be collected and accurately handled. To assist the engineer and engineering student in this power system planning, computers and highly developed computer software are used such as Power World Simulator. In this paper, Power World Simulator power flow programs compute the voltage magnitudes, phase angles, and transmission-line power flows for WSCC nine bus system under steady-state operating conditions. Other results, including transformer tap settings and generator reactive power outputs, equipment losses are also computed.

2. POWER FLOW ANALYSIS:

The power flow analysis is the computation of voltage magnitude and phase angle at each bus in a power system under balanced three-phase steady-state conditions. As a by product of this calculation, real and reactive power flows in equipment such as transmission lines and transformers, as well as equipment losses, can be computed.

The starting point for a power flow analysis is a single line diagram of the power system, from which the input data for computer solutions can be obtained. Input data consist of bus data, transmission line data, and transformer data. As shown in Fig. 1, the following four variables are associated with each bus n: voltage magnitude V_i, phase angle δ_i, net real power P_i, and reactive power Q_i supplied to the bus. At each bus, two of these variables are specified as input data, and the other two are unknowns to be computed by the power flow program. For convenience, the power delivered to bus i in Fig. 1 is separated into generator and load terms. That is

$$P_i = P_{Gi} - P_{Li} \tag{1}$$

$$Q_i = Q_{Gi} - Q_{Li} \tag{2}$$

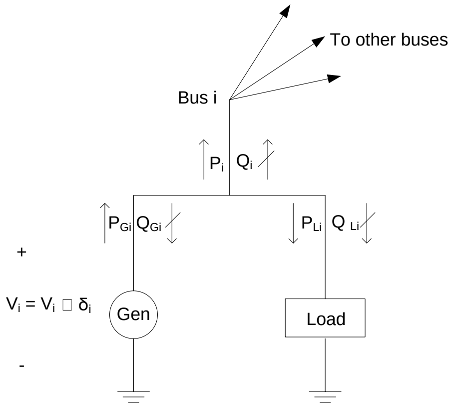

Fig. 1 Bus variables V_i, δ_i, P_i, and Q_i

Each bus i is categorized into one of the following three bus types;

1. Swing bus (or slack bus): There is only one swing bus, which for convenience is numbered bus 1 in this paper. The swing bus is a reference bus for which $V_1\angle\delta_1$, typically $1.0\angle 0$ H per unit, is input data. The power flow program computes P_1 and Q_1.

2. Load (PQ) bus: P_i and Q_i are input data. The power flow program computes V_i and δ_i. Most buses in a typical power flow program are load buses.

3. Voltage controlled (PV) bus (or Generator bus): P_i and V_i are input data. The power flow program computes Q_i and δ_i. Examples are buses to which generators, switched shunt capacitors, or static var systems are connected. Maximum and minimum var limits Q_{Gimax} and Q_{Gimin} that this equipment can supply are also input data. If an upper or lower reactive power limit is reached, then the reactive power output of the generator is held at the limit, and the bus is modeled as a PQ bus. Another example is a bus to which a tap-changing transformer is connected; the power-flow program then computes the tap setting. Note that when bus k is a load bus with no generation, $P_i = - P_{Li}$ is negative; that is, the real power supplied to bus i in Fig. 1 is negative. If the load is inductive, $Q_i = - Q_{Li}$ is negative.

Table I
Bus classification

No.	Type of Bus	Variables			
		P	Q	IVI	δ
1	Slack Bus	Unknown	Unknown	Known	Known
2	Load Bus (PQ)	Known	Known	Unknown	Unknown
3	Generator Bus (PV)	Known	Unknown	Known	Unknown

A. Application of the Newton-Raphson Method to Power Flow Analysis

The numerical analysis involving the solution of algebraic simultaneous equations forms the basis for solution of the performance equations in computer aided electrical power system analyses e.g. for load flow analysis. The first step in performing load flow analysis is to form the Y_{bus} admittance using the transmission line and transformer input data. The nodal equation for a power system network using Y_{bus} can be written as follows;

$$I = Y_{bus} V \tag{3}$$

The nodal equation can be written in a generalized form for an i bus system

$$I_i = \sum_{j=1}^{n} Y_{ij} V_j \quad \text{for } i = 1,2,3,n \tag{4}$$

The complex power delivered to bus i is

$$P_i + jQ_i = V_i I_i \tag{5}$$

$$I_i = \frac{P_i - jQ_i}{V_i^*} \tag{6}$$

Substituting for I_i in terms of P_i & Q_i , the equation gives

$$\frac{P_i - jQ_i}{V_i^*} = V_i \sum_{j=1}^{n} Y_{ij} - \sum_{j=1}^{n} Y_{ij} V_j \qquad j \neq i \tag{7}$$

The above equation uses iterative techniques to solve load flow problems. Hence, it is necessary to review the general forms of the various solution methods; Gauss-Seidel, Newton-Raphson and Fast decoupled load flow.

Newton-Raphson method was named after Isaac Newton and Joseph Raphson. The origin and formulation of Newton-Raphson method was dated back to late 1960s. It is an iterative method which approximates a set of non-linear simultaneous equations to a set of linear simultaneous equations using Taylor's series expansion and the terms are limited to the first approximation. It is the most iterative method used for the load flow because its convergence characteristics are relatively more powerful compared to other alternative processes and the reliability of Newton-Raphson approach is comparatively good since it can solve cases that lead to divergence with other popular processes. If the assumed value is near the solution, then the result is obtained very quickly, but if the assumed value is farther away from the solution then the method may take longer to converge. This is another iterative load flow method which is widely used for solving nonlinear equation.

The admittance matrix is used to write equations for currents entering a power system.

Equation (4) is expressed in a polar form, in which j includes bus i ;

$$I_i = \sum_{j=1}^{n} |Y_{ij}|\,|V_j|\,\angle\theta_{ij} + \delta_j \qquad (8)$$

The real and reactive power at bus i is ;

$$P_i - jQ_i = V_i^{*}\ I_i \qquad (9)$$

Substituting for Ii in Equation (9) from Equation (8);

$$P_i - jQ_i = |V_i|\angle{-\delta_i}\ \sum_{j=1}^{n} |Y_{ij}|\,|V_j|\,\angle\theta_{ij} + \delta_j \qquad (10)$$

The real and imaginary parts are separated;

$$P_i = \sum_{j=1}^{n} |V_i|\,|V_j|\,|Y_{ij}| \cos(\theta_{ij} - \delta_i + \delta_j) \qquad (11)$$

$$Q_i = -\sum_{j=1}^{n} |V_i|\,|V_j|\,|Y_{ij}| \sin(\theta_{ij} - \delta_i + \delta_j) \qquad (12)$$

The above Equation (11) and (12) constitute a set of non-linear algebraic equations in terms of |V| in per unit and δ in radians. Equation (11) and (12) are expanded in Taylor's series about the initial estimate and neglecting all higher order terms, the following set of linear equations are obtained.

$$\left[\begin{array}{c} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \hline \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{array}\right] = \left[\begin{array}{ccc|ccc} \frac{\partial P_2^{(k)}}{\partial \delta_2^{(k)}} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n^{(k)}} & \frac{\partial P_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2^{(k)}} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n^{(k)}} & \frac{\partial P_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial P_n^{(k)}}{\partial |V_n|} \\ \hline \frac{\partial Q_2^{(k)}}{\partial \delta_2^{(k)}} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n^{(k)}} & \frac{\partial Q_2^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_2^{(k)}}{\partial |V_n|} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2^{(k)}} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n^{(k)}} & \frac{\partial Q_n^{(k)}}{\partial |V_2|} & \cdots & \frac{\partial Q_n^{(k)}}{\partial |V_n|} \end{array}\right] \left[\begin{array}{c} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \hline \Delta |V_2^{(k)}| \\ \vdots \\ \Delta |V_n^{(k)}| \end{array}\right]$$

In the above equation, the element of the slack bus variable voltage magnitude and angle are omitted because they are already known. The element of Jocobian matrix are obtained after partial derivatives of equations (11) and (12) are expressed which gives linearized relationship between small changes in voltage magnitude and voltage angle. The equation can be written in matrix form as;

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_3 \\ J_2 & J_4 \end{bmatrix} \begin{bmatrix} \Delta\delta \\ \Delta |V| \end{bmatrix} \qquad (13)$$

J_1, J_2, J_3, J_4 are the elements of the Jocobian matrix.

The difference between the schedule and calculated values known as power residuals for the terms $\Delta P_i^{(k)}$ and $\Delta Q_i^{(k)}$ is represented as;

$$\Delta P_i^{(k)} = P_i^{sch} - P_i^{(k)} \tag{14}$$

$$\Delta Q_i^{(k)} = Q_i^{sch} - Q_i^{(k)} \tag{15}$$

The new estimates for bus voltage are;

$$\delta^{(k+1)} = \delta_i^{(k)} + \Delta \delta_i^{(k)} \tag{16}$$

$$|V^{(k+1)}| = |V_i^{(k)}| + \Delta|V_i^{(k)}| \tag{17}$$

B. Description of Power World Simulator to Power Flow Analysis

Power flow analysis can be better understood using computer software packages. One of the many power flow software packages that can be used is Power World. This package allows for the easy simulation of bus systems that would take a significant amount of time if done by hand. One such system is WSCC 9 bus model. This is a relatively small and simple power system. Understanding how this system works will assist students in understanding load flow analysis. The results of changes to the system can be seen quickly in Power World, further aiding students' learning process. Power World's wide range of products provide the tools needed by transmission planners, power marketers, system operators and trainers, educators, and anyone else desiring access to power system information and analysis in a user friendly format.

The single line diagrams are animated for the benefit of the users. The integrated drawing tools give an easy and fast approach to creating single line diagrams, circuit diagrams where a single line is shown to represent three phases of a power system. Power World uses the Newton-Raphson iteration method, which provides an efficient and accurate solution. It also computes the Jacobian (Admittance Matrix).

3. Power Flow Analysis Results using Power World Simulator :

A. Input Data of WSCC 9 Bus Power System Model

Fig. 2 shows single line diagram of WSCC nine bus power system model. As shown in Table II, bus 1, to which a generator is connected, is the slack bus. Buses 2 and 3, to which generators are connected, are generator buses. Buses 4, 5, 6, 7, 8 and 9 are load buses. The input data and unknown data of WSCC 9 bus power system model are shown in Tables II, III, IV, and V.

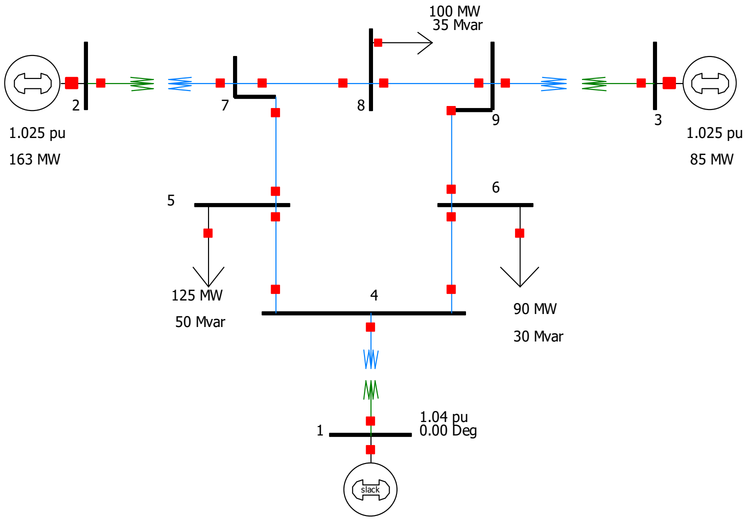

Fig. 2 Test model of WSCC 9 bus power system using PowerWorld simulator

Table II
Bus input data of WSCC 9 bus power system model

Bus	Type	V per unit	δ Degrees	P_G per unit	Q_G per unit	P_L per unit	Q_L per unit
1	Slack	1.04	0	-	-	0	0
2	Generator	1.025	-	1.63	-	0	0

3	Generator	1.025	-	0.85	-	0	0
4	Load	-	-	0	0	0	0
5	Load	-	-	0	0	1.25	0.5
6	Load	-	-	0	0	0.9	0.3
7	Load	-	-	0	0	0	0
8	Load	-	-	0	0	1	0.35
9	Load	-	-	0	0	0	0

(* S_{base} = 100 MVA , * P_{base} = 100 MW)

Table III
Line input data of WSCC 9 bus power system model

Bus to Bus	R' per unit	X' per unit	G'/2 per unit	B'/2 per unit	Max MVA per unit
4 – 5	0.010	0.085	0	0.088	1
4 – 6	0.017	0.092	0	0.079	1
5 – 7	0.032	0.161	0	0.153	1
6 – 9	0.039	0.170	0	0.179	1
7 – 8	0.0085	0.072	0	0.0745	1
8– 9	0.0119	0.1008	0	0.1045	1

Table IV
Transformer input data of WSCC 9 bus power system model

Bus to Bus	R per unit	X per unit	Maximum MVA per unit	Off norminal turn Ratio	Phase shift degrees	Norminal (kV)
1– 4	0	0.0576	1	1.0	0	16.5/230
2– 7	0	0.0625	2	1.0	0	18/230
3– 9	0	0.0586	1	1.0	0	13.8/230

Table V
Bus input data and unknown data of WSCC 9 bus power system model

Bus	Input Data	Unknowns
1	$V_1 = 1.04, \delta_1 = 0$	P_1, Q_1
2	$P_{G2} = 1.63, V_2 = 1.025$	Q_{G2}, δ_2
3	$P_{G3} = 0.85, V_2 = 1.025$	Q_{G3}, δ_3
4	$P_{L4} = 0, Q_{L4} = 0$	V_4, δ_3
5	$P_{L5} = 1.25, Q_{L5} = 0.5$	V_5, δ_5
6	$P_{L6} = 0.9, Q_{L6} = 0.3$	V_6, δ_6
7	$P_{L7} = 0, Q_{L7} = 0$	V_7, δ_7
8	$P_{L8} = 1, Q_{L8} = 0.35$	V_8, δ_8
9	$P_{L9} = 0, Q_{L9} = 0$	V_9, δ_9

B. Animated Results of WSCC 9 Bus Power System (Case Study I)

A Newton-Raphson power flow analysis will be performed on the WSCC 9 bus power system by using the Power World Simulator described in Fig. 3. Generator 1 is set up to be the slack generator at bus 1. Generator 2 is set up to be 163 MW output at bus 2 and Generator 3 is set up to be 85 MW output at bus 3. The connected loads are 125 MW, 50 MVAR (inductive) at bus 5, 90 MW , 30 MVAR (inductive) at bus 6 and 100 MW, 35 MVAR at bus 8. The animated results of this power flow are shown in Fig. 3. The resulting bus voltages and phase angles are also shown on the single line diagram. The resulting power flows for each transmission line feeding the connected loads are also displayed. The pie charts associated with each transmission line, provide the indication of transmission line loading.

The animated detail results from the model explorer dialog when solving the Newton-Raphson power flow analysis are shown in Tables VI, VII, and VIII.

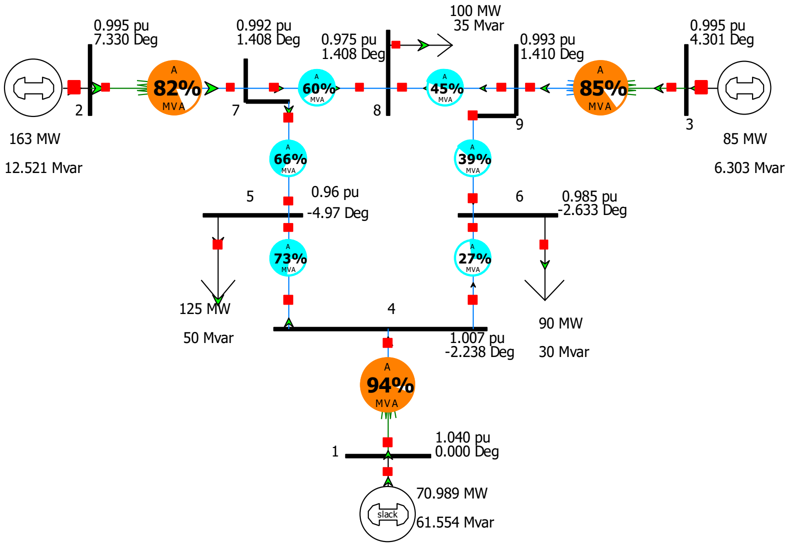

Fig. 3 Animated results of power flow analysis for WSCC 9 bus power system using PowerWorld simulator

Table VI
Branches state results data of WSCC 9 bus power system model

From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	MW From	Mvar From	MVA From	Lim MVA	% of MVA Limit (Max)	MW Loss	Mvar Loss
1	slack bus	4	4	1	Closed	Transformer	YES	71	61.6	94	100	94	0	4.7
2	2	7	7	1	Closed	Transformer	YES	163	12.5	163.5	200	81.7	0	16.87
3	3	9	9	1	Closed	Transformer	YES	85	6.3	85.2	100	85.2	0	4.3
4	4	5	5	1	Closed	Line	NO	59.5	39.2	71.3	100	73.1	0.54	-3.98
4	4	6	6	1	Closed	Line	NO	11.4	17.6	21	100	27.4	0.1	-7.29
5	5	7	7	1	Closed	Line	NO	-66	-6.8	66.3	100	67.5	1.5	-7.13
6	6	7	7	1	Closed	Line	NO	-39.5	-2.4	39.6	0	0	0.64	-14.55
6	6	9	9	1	Closed	Line	NO	-39.2	-2.6	39.2	100	41.6	0.63	-14.75
7	7	8	8	1	Closed	Line	NO	58.6	14.5	60.4	100	61.3	0.32	-4.46
7	7	9	9	1	Closed	Line	NO	-3.3	-6.4	7.2	0	0	0	-0.18
8	8	9	9	1	Closed	Line	NO	-41.7	-16.1	44.7	100	44.7	0.23	-8.14

Table VII
Bus results data of WSCC 9 bus power system model

Number	Name	Area Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar	Area Num	Zone Num
1	slack bus	1	16.5	1.04	17.16	0			70.99	61.55	1	1
2	2	1	18	0.995	17.91	7.33			163	12.52	1	1
3	3	1	13.8	0.995	13.731	4.3			85	6.3	1	1
4	4	1	230	1.00668	231.536	-2.24					1	1
5	5	1	230	0.96497	221.944	-4.97	125	50			1	1

6	6	1	230	0.985	226.551	-2.63	90	30			1	1
7	7	1	230	0.99243	228.259	1.41					1	1
8	8	1	230	0.97511	224.275	-1	100	35			1	1
9	9	1	230	0.99255	228.287	1.41					1	1

Table VIII
Generator results data of WSCC 9 bus power system model

Number of Bus	Name of Bus	Status	Gen MW	Gen Mvar	Set Volt	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Part. Factor
1	slack bus	Closed	70.99	61.55	1.04	YES	0	1000	-9900	9900	10
2	2	Closed	163	12.52	0.995	YES	0	1000	-9900	9900	10
3	3	Closed	85	6.3	0.995	YES	0	1000	-9900	9900	10

C. Animated Results of WSCC 9 Bus Power System with Power Factor Correction (Case Study II)

For this analysis, a power factor correction capacitor (PFC) rated at 25 MVAR (capacitive) was connected to the load bus 5 of WSCC 9 bus power system model. The purpose of the capacitor was to increase the voltage at load bus 5 by providing leading VARs to the power system network. The input data and unknown data of WSCC 9 bus power system model are shown in Tables II, III, IV, and V. The results of this simulation are depicted in Fig. 4. It is easily determined from the results that the capacitor provides all of the necessary VARs to the power system network. Some of the capacitive VARs are consumed by the connected load, the remaining VARs are provided to the power system network. The voltage at the load bus 5 is increased. With the simulator in animation mode, this is accomplished by clicking the switch connected with the PFC. All results are immediately displayed on the power system single line diagram. The animated detail results from the model explorer dialog when solving the Newton-Raphson power flow analysis are shown in Tables IX, X, and XI.

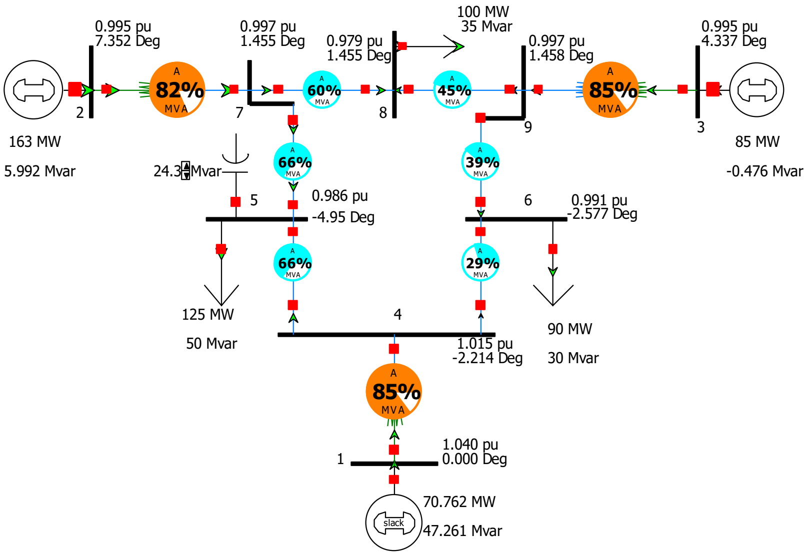

Fig. 4 Animated results of power flow analysis for WSCC 9 bus power system with PFC using PowerWorld simulator

Table IX
Branches state results data of WSCC 9 bus power system model with PFC

From Number	From Name	To Number	To Name	Circuit	Status	Branch Device Type	Xfrmr	MW From	Mvar From	MVA From	Lim MVA	% of MVA Limit (Max)	MW Loss	Mvar Loss
1	slack bus	4	4	1	Closed	Transformer	YES	70.8	47.3	85.1	100	85.1	0	3.86
2	2	7	7	1	Closed	Transformer	YES	163	6	163.1	200	81.7	0	16.8
3	3	9	9	1	Closed	Transformer	YES	85	-0.5	85	100	85.1	0	4.28
4	4	5	5	1	Closed	Line	NO	59.4	23.6	64	100	65.7	0.42	-5.24
4	4	6	6	1	Closed	Line	NO	11.3	19.8	22.8	100	29.3	0.12	-7.32

5	5	7	7	1	Closed	Line	NO	-65.9	3.2	66	100	68.3	1.47	-7.65
6	6	7	7	1	Closed	Line	NO	-39.6	-1.4	39.6	0	0	0.64	-14.73
6	6	9	9	1	Closed	Line	NO	-39.2	-1.5	39.2	100	42	0.63	-14.93
7	7	8	8	1	Closed	Line	NO	58.6	14.4	60.4	100	61.3	0.32	-4.54
7	7	9	9	1	Closed	Line	NO	-3.2	-1	3.4	0	0	0	-0.18
8	8	9	9	1	Closed	Line	NO	-41.7	-16	44.7	100	44.7	0.23	-8.24

Table X
Bus results data of WSCC 9 bus power system model with PFC

Number	Name	Area Name	Nom kV	PU Volt	Volt (kV)	Angle (Deg)	Load MW	Load Mvar	Gen MW	Gen Mvar	Switched Shunts Mvar	Area Num	Zone Num
1	slack bus	1	16.5	1.04	17.16	0			70.76	47.26		1	1
2	2	1	18	0.995	17.91	7.35			163	5.99		1	1
3	3	1	13.8	0.995	13.731	4.34			85	-0.48		1	1
4	4	1	230	1.01458	233.354	-2.21						1	1
5	5	1	230	0.98625	226.838	-4.95	125	50			24.32	1	1
6	6	1	230	0.99109	227.95	-2.58	90	30				1	1
7	7	1	230	0.99651	229.197	1.45						1	1
8	8	1	230	0.97926	225.23	-0.93	100	35				1	1
9	9	1	230	0.99654	229.204	1.46						1	1

Table XI
Generator results data of WSCC 9 bus power system model with PFC

Number of Bus	Name of Bus	Status	Gen MW	Gen Mvar	Set Volt	AVR	Min MW	Max MW	Min Mvar	Max Mvar	Part. Factor
1	slack bus	Closed	70.76	47.26	1.04	YES	0	1000	-9900	9900	10
2	2	Closed	163	5.99	0.995	YES	0	1000	-9900	9900	10
3	3	Closed	85	-0.48	0.995	YES	0	1000	-9900	9900	10

4. CONCLUSION:

This paper described power flow analysis of WSCC 9 bus power system model using software tool, Power World simulator. The simulator tool greatly enhances the electrical engineering student’s ability to visualize Power flows contributions in a power system network. This power flow analysis was created using the student version of Power World simulator that is limited to 13 buses. The full version is relatively inexpensive and gives the user the capability to model much larger and complex power system networks.

In this paper, the power flows analysis for WSCC 9 bus power system model was animated both case study I and case study II by using the model-based Newton-Raphson in Power World simulator .Through these studies, the branches state results, buses and generator results data are described. Capacitive shunt compensation is used to regulate the voltage angle and magnitude. The results of the power flow analysis after compensation show a significant reduction in the total system real power loss and the buses voltages increased. The voltage angles are correspondingly improved upon.

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