International Journal of Power System Operation and Energy Management

Volume 1 | Issue 1 Article 15

July 2011

A New Formulation for Load Flow Solution of Power Systems With Series FACTS Devices

P. sravan Kumar
GMRIT, Rajam-532127, AP, India, sravankumar228@gmail.com

A. Appa Rao
GMRIT, Rajam-532127, AP, India, apparao.a@gmrit.org

K. Sarat Kumar Dr.
GMRIT, Rajam-532127, AP, India, saratkumar.sahu@gmail.com

Recommended Citation

Kumar, P. sravan; Rao, A. Appa; and Kumar, K. Sarat Dr. (2011) "A New Formulation for Load Flow Solution of Power Systems With Series FACTS Devices," *International Journal of Power System Operation and Energy Management*: Vol. 1 : Iss. 1 , Article 15.
Available at: https://www.interscience.in/ijpsoem/vol1/iss1/15

A New Formulation for Load Flow Solution of Power Systems With Series FACTS Devices

P. sravan Kumar[#1], **A. Appa Rao**[#2], **Dr. K. Sarat Kumar**[#3]
[#]Dept of EEE, [*] prof in Dept of EEE
GMRIT, Rajam-532127, AP, India
[1] sravankumar228@gmail.com, [2]apparao.a@gmrit.org, [3]saratkumar.sahu@gmail..com

Abstract – this paper addresses the solution of load flow equations for a power system with series flexible ac - transmission systems(FACTS) devices. A novel formulation of equations using dual state variables (current magnitude and angle) and dual controlvariables (series injected real power and series voltage in quadrature with current) for series devices is proposed. These specifications can be related to transmission line loading and device limits.Specifications like power flow through a series device can also be handled using this formulation. The load flow equations are solved using Newton-Raphson technique. A decoupled formulation is also proposed. Case studies are carried out on IEEE test systems withseveral types of specifications to validate the method.

KEYWORDS- *flexible ac transmission systems, load flow.*
(Footnotes)

I. INTRODUCTION

The advent of the flexible ac transmission systems(facts) devices has given additional leverage to control a power system. While FACTS devices like static var compensator (SVC) and thyristor controlled series compensator(TCSC) are variable reactance devices based on thyristors, the new generation of devices like static synchronous compensator (STATCOM), static synchronous series compensator (SSSC),unified power-flow controller (UPFC), and interline power flow controller (IPFC) are based on voltage sourceconverter(VSC)STATCOM and SVC are shunt connected; SSSC,IPFC, and TCSC are ser ies connected; and UPFC is a hybridconnected (i.e., have components connected both in series and shunt) FACTS device.

With the help of FACTS devices, it is possible to regulate Real and reactive power flows in the network. In this context,There is a need to develop analytical tools in order to gauge the effectiveness of these devices. In particular, existing programs for load flow and stability studies need to be modified to incorporate these devices. For the incorporation of FACTS devices in load flow studies, the following issues are important.
1) Formulation of equations.
- choice of state variables (nodal voltages and angles in a conventional load flow);
- choice of control/specified variables (shunt real and reactive power injections in a conventional load flow);

These choices are dictated by the basic operating characteristics, control, and limits of the devices.
2) Methods of solution:
Simultaneous or unified method : in this mehod all equations are combined into one set of non linear algebraic equation. A Jacobian matrix is then constructed and Newton method is used to solve these equations. However, it may be inconvenient to implement, as the incorporation of a FACTS device requires significant modifications inexisting load flow programs.

Sequential or Alternate method : in this method the equations are sepeated into those corresponding to the facts device Specifications and the rest of the power balance equations. The equations are solved separately and sequentially. This method allows the minor modification of the existing software. the conventional load flow formulation is subpart of the main algorithem Load flow formulation and solution methodology for series
FACTS devices in the previous literature mainly pertains to
variable series reactance. Noroozian and Anderson [3] use
real power flow as a specified variable and the reactance of a TCSC as a state variable. Two coupled load flow and line flow equations are solved sequentially. First, one load flow solution is carried out by NR method by using the usual Jacobian matrix. The line power flow equation is then solved iteratively using the solution of the load flow equations to get updated values of series compensating reactance. These variables are used to carry out next load flow solution. The procedure is repeated till both solutions converge. In the method proposed by Fuerte–Esquivel and Acha [4], for each controllable series reactance, one extra line flow mismatch equation is augmented to the original NR load flow

equations along with one extra state variable. It is observed that this unified approach is more robust and convergence is obtained within half the number of iterations as that required by the sequential approach. Gotham and Heydt [5] consider an extra fictitious bus for which real power specification is given. However, the reactive power specification and voltage magnitude at that bus are not known and are obtained from another set of nonlinear equations which are solved separately.

This paper presents a novel formulation of load flow equations for series devices like sssc and tcsc, using dual state variables (current magnitude and angle) and dual control variables (injected series real power and series voltage in quadrature with the line current) The elements of the various submatrics are defined as follows:

The elements of the various submatrics are defined as follows:

The elements of the various submatrics are defined as follows:

1) The following specifications which are useful in a load-Flow study can be easily handled:

a) current magnitude in a branch (which is related to thermal loading of a line and FACTS device rating);

b) series voltage injection (related to limits of TCSC and control of SSSC);

c) series reactive power injection.

2) Series power flow specification can also be handled by minor modification of the formulation.

3) While the main thrust is to solve loadflow equations with series reactive power devices like SSSC and TCSC, devices like UPFC and IPFC can also be accommodated in the formulation.

The load flow equations are solved by the simultaneous method using the Newton–Raphson technique, which has a good convergence characteristics. The formulation is also amenable for decoupling. Case studies are presented for IEEE 14- and 162-bus systems to validate the method.

phase angle of voltage at bus;

β phase angle of current flowing in a branch;
I magnitude of current flowing in a branch;
Ir shunt injected reactive current;
V bus voltage magnitude;
Vp series injected voltage in phase with line current;
Vr series injected voltage in quadrature with line current;
Psh shunt injected real power;
Pser series injected real power;
Pf real power flow in a branch;
Qsh shunt injected reactive power;
Qser series injected reactive power;
magnitude of element in bus admittance matrix;

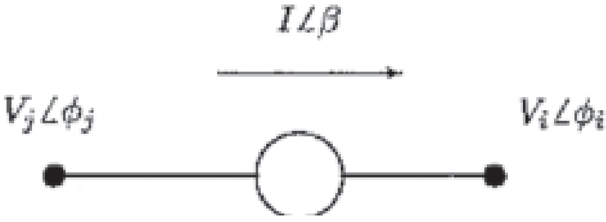
angle of element in bus admittance matrix;
nj set of buses connected to bus by branches which do not have series FACTS devices;
rj set of branches connected to bus where series FACTS devices are connected;
= J1

Xbr inductive compensating reactance in a branc h consider a series facts controller as shown in figure .1

the real power and voltage in quadratuer with the line current injected by the series device are given by

pser = VpI =-Vj I cos(-â)+ Vi cos(ϕ i-â)

Vr =Qser/I==VjIsin(-â) + Vi sin(i-â)



$$\text{Pser} = \sum_{i\in nj} VjVi\left|Yij\right|\cos(\phi j-\phi i-\theta ji)+\sum_{l\in rj} VjIl\cos(\phi j-\beta l)$$

At any bus j, the net injected power is given by

Note: In the above equations, a series FACTS device is considered tpbe aseperate branch in the nework. Ihis branch is not ccounted for in the bus admittance matrix

Now,for the application of newton raphson method,the linearized real power and reactive power mismatch equations can be written as follows:

$$\begin{bmatrix} \nabla Psh \\ \nabla IR \\ \nabla Pser \\ \nabla VR \end{bmatrix} \begin{bmatrix} A11 & A12 & A13 & A14 \\ A21 & A22 & A23 & A24 \\ A31 & A32 & A33 & A34 \\ A41 & A42 & A43 & A44 \end{bmatrix} \begin{bmatrix} \nabla\phi \\ \nabla V \\ \nabla\beta \\ \nabla I \end{bmatrix}$$

$$\begin{bmatrix} \nabla\phi \\ \nabla V \\ \nabla\beta \\ \nabla I \end{bmatrix}$$

$\nabla Psh = Psh^{spec} — psh^{cal}$; $\nabla Pser = pser^{spe} — pser^{cal}$

$\nabla IR = Ir^{spe} — Ir^{cal}$; $\nabla VR = Vr^{spe} — Vr^{cal}$

The elements of the various submatrics are defined as follows:

$\partial Pshi / \partial\phi$

A11(i,j)= ;A12(i,j)= ;A13(i,j)=

A14(i,j)= ;A21(i,j)= ; A22(i,j)=

A23(i,j)= ; A24(i,j)= ;A31(i,j)=

A32(i,j)= ; A33(i,j)= ;A34(i,j)=

Fig.3 convgence chhareceristic:14-bus system I specified

A41(i,j)= ;A42(i,j)= ;A43(i,j)=

IV. LOAD FLOW SOLUTION

For obtaining a load flow solution, the following formu-lations are considered.

Formulation

The formulation given in the previous section can be used to implement a N-R load flow. This requires augmentation of the Jacobian in a conventional load flow. The Jacobian in (5) is used depending on whether or specification is given. Since series devices are likely to be present on only a few lines, a majority of the terms in the Jacobian are similar to a conventional load flow Jacobian.

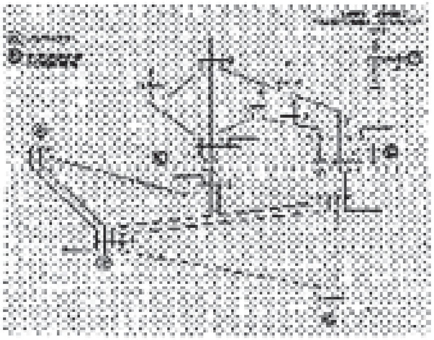


Fig.2. line diagrame of 14- bus test system

A. IEEE 14-Bus System

Load flow studies are carried outonthissystem(seefigure.2) for various specifications as given below

1) Pser—I or Pser—Pf specification

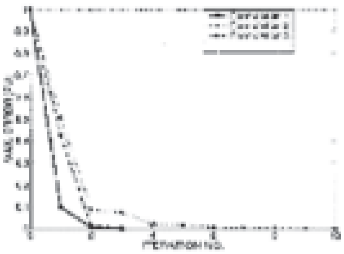


Fig.3 convergence ciharacteristic: 14-bus system I specified

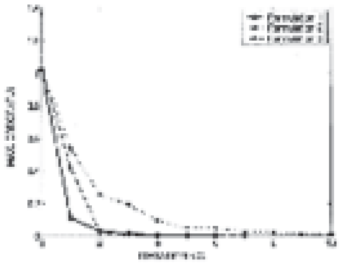


Fig.4 convergence ciharacteristic: 14-bus system Pf specified

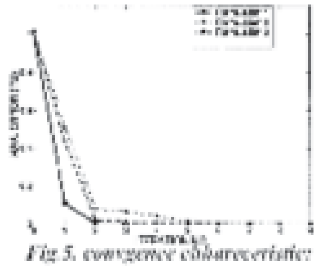


Fig 5. convergence ciharacteristic: 14-bus system Qser specified

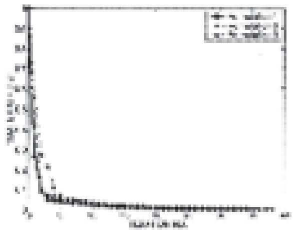


Fig.5 convergence characteristics : 14-bus system: qser and terminal bus voltage limit specified

In this case ,a sssc is connected in line 2-3 at bus number 2. The desired line current is 1 p.u. No limits are set on themag-nitude of . The convergence characteristics [i.e., the maxi-mum error (mismatch) versus the number of iterations] are plotted in Fig. 3. To increase the line current from 0.7p.u. (un compensated case) to1p.u., the Vr required is 0.14 p.u. Therefore the equi-valent capacitive reactance is 0.14 p.u.Thevoltage magn-itudes of the buses across which the SSSC is conne- cted are 1.045 p.u. (bus 2)and 1.0196 p.u. (bus 15). Note that bus number 15 is the extra bus added in the network and series device is between buses 2 and 15. If instead of a I specifica-tion ,Pf specification of 1.0 p.u.is given ,then the the modified procedure outlined intheprevious section is used. The convergence characteristic is shown in Fig. 4. The conv-erged value of the injected voltage is 0.13 p.u.,while the bus voltages are 1.045 p.u. (bus 2) and 1.0253 p.u. (bus 15).

2). Pser –Qser specification

In this case, a SSSC injects 0.1-p.u. reactive power in the line 2–4 at bus number 2. The load flow solution gives a line current of 0.89 p.u. (line current is 0.53 p.u. when SSSC is ab- sent). Theconvergence characteristics are plotted in Fig. 5. The voltage magnitudes of the buses across which the SSSC is connected are 1.04 (bus 2) and 1.01 (bus 15). If the voltage magnitude at the latter bus is to be limited to a value of 1 p.u., then the (11) and (13) are used to change the Qser specification. The reactive power settles to avalue of 0.13 p.u. Note that the convergence performance (see Fig. 6) is degraded (it is slow near the true solution). If áQ is multiplied by a factor of 2, then the convergence is improved and the number of iterations is reduced by approximately half for the same tolerance.

3). (Pser-Vr) - (Pser—I)specification.

Two SSSCs are considered here: the first SSSC is con-nected in line 2–4 at bus 2 which is assumed to inject Vr= -0.05 p.u. .The second SSSC is connected in a line 2–3 and the desired current in the line 2–3 is 0.95 p.u. The Vr requirement in this case exceeds the specified limit (-0.1 p.u.). consequently,this sssc iss changed to Vr specified type with the specified voltage set to the lim-iting value. The current in line 2–3 is increased from 0.7 p.u. (when SSSC is absent) to 0.86 p.u. Since the other SSSC hits its voltage injection limit, the current magni-tude is 0.86 p.u. (which is less than the desired current).Fig. 3 shows the convergence characteristics for this case.

VII. CONCLUSIONS AND FUTURE WORK

In this paper, a novel dual formulation for load flow studies is proposed. It involves use of dual variables and specifications for series connected devices in much the same way as for a conventional load flow. The speci-fications can be related easily to device limits and trans-mission line loading. Equations are solved using N-R method. Simplification and decoupling of the Jacobian is also tried. From the case studies presented, the following conclusions are drawn.

1) Rate of convergence for N-R method is good for all types Of speccifications
2) Convergence is robust to initial guess of device current magnitude

3) For series reactive power devices, power flow specification can be used instead of current magnitude specification and the convergence characteristics are similar.
4) For series reactive power devices, bus voltage limit canalso be handled by making minor modifications. However, convergence rate is slow near the true solution.
5) Devices like UPFC and IPFC can be incorporated for certain specifications.

The dual formulation presents possibilities for future work in
other studies related to the load flow. In particular, one can an-analyze sensitivity and controllability of current flows to series reactive power injection in various lines of a network. Also, the effect of series reactive power injection on voltage stability can be analyzed using this formulation.

References

[1] N. G. Hingorani and L. Gyugyi, Understanding FACTS: Concepts and Technology of Flexible AC Transmission Systems. New York: IEEE Press, 2000.

[2] S. Arabi and P. Kundur, “A versatile FACTS device model for power flow and stability simulations,” IEEE Trans. Power Syst., vol. 11, pp. 1944–1950, Nov. 1996.

[3] M. Noroozian and G. Anderson, “Power flow control by use of con- trollable series components,” IEEE Trans. Power Delivery, vol. 8, pp. 1420–1429, July 1993.

[4] C. R. Feurte Esquivel and E. Acha, “A Newton-type algorithm for the control of power flow in electrical power networks,”IEEE Trans.

[5] D. J. Gotham and G. T. Heydt, “Power flow control and power flow studies for system with FACTS devices,” IEEE Trans. Power Syst., vol. 13, pp. 60–66, Feb. 1998.