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Modeling of UPFC and DG by the Current Based Model

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Abstract

This paper deals with the steady state modeling of unified power flow controller (UPFC). Since current limitations are determinant to FACTS apparatus design, the proposed current based model (CBM) assumes the current as variable, allowing easy manipulation of current restrictions in optimal power flow evaluations. The performances of current based model (CBM) and of the power injection model (PIM) are compared through a Quasi-Newton optimization approach. The performance of a medium size network with 39 busbars is studying from the point of view network having only UPFC and the network having UPFC and DG. For the Two networks active power losses, reactive power losses are compared.

Keywords- FACTS, Optimal power flow, Quasi-Newton Raphson method, UPFC, CBM, DG.

I. INTRODUCTION

The continuing rapid development of high-power semiconductor technology now makes it possible to control electrical power systems by means of power electronic devices [1]. These devices constitute an emerging technology called FACTS (flexible alternating current transmission systems) [2]. The FACTS technology opens up new opportunities for controlling the both types of powers and enhancing the usable capacity of present transmission systems. The possibility that power through a line can be controlled enables a large potential of increasing the capacity of lines. This opportunity is arises through the ability of FACTS controllers to adjust the power system electrical parameters including series and shunt impedances, current, voltage, phase angle, and the damping oscillations etc. The implementation of such equipments requires the different power electronics-based compensators and controllers [5].

Power flow studies and escalation techniques are indispensable tools for the safe and economic operation of large electrical systems. The UPFC is one of the most complete apparatus of this new technological family, allowing the regulation of active and reactive powers, substantially enlarging the operative flexibility of the system.[1]-[5]

The employed models [7] in represent the active elements through equivalent passive circuits, including the power balance equation. In the passive model consists of a susceptance and an ideal voltage transformer and the fundamental power balance equation is intrinsically included. Voltage source models employed in [8]-[10] consist of series and shunt voltages offered in the equations as control variables.

The model illustrated [11], known as power injection model (PIM), is quite spread in the literature, representing the effect of active elements by equivalent injected powers. In the traditional models, the current is not clearly treated in the equations. As in the design of FACTS converters one of the main limitations lies on current limitation, it is expedient to have a model that uses the current as a variable, which will be the purpose of this project.

The load flow studies are done through current based model only but for good results and power quality improvement we are introducing the DG's .Depending upon the voltage constraints the dg location is founded i.e, The voltage at the node exceeds the maximum voltage, at that particular node DG is placed. After DG placement Voltage Profile is improved and power losses are reduced.

II. CURRENT BASED MODEL OF UPFC

The developed model signifies the UPFC in substantial state, introducing the current in the series converter as variable.

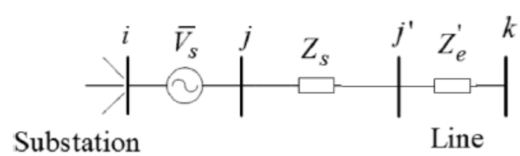

Fig1: UPFC in the Network

Let us consider busbars i and k existent in the transmission line where the UPFC will be located, with impedance. Busbars j and j' are created in order to include the UPFC in the system. The series impedance of UPFC coupling transformer and the transmission line are added, resulting in the equivalent impedance connected to the internal node and node is eliminated. This alliance is quite simple, even in case of two port lines reoffered by π circuits.

The equivalent network is offered in Fig. 2, with the series voltage inserted between busbars *i* and *j*

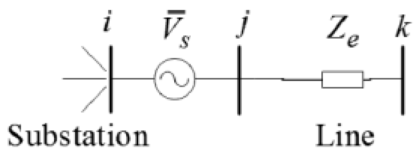

Fig. 2. Equivalent model of UPFC in the electric network.

Current Ī introduces two variables in the network magnitude of current (I), phase angle of the current (φ).Due to this current all parameters are varied i.e: injected power due to current Ī, power balance, series voltage equations and jacobian matrix. How these parameters vary when the current is introduced in the network shown in the below.

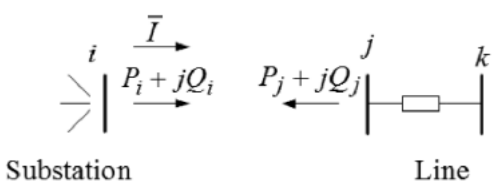

Fig. 3. Injected power due to current in busbars.

A. Injected Power Due to Current

The power intake of the system load at busbar is called $S_i^{\,0}$.Additional powers, due to current, are easily calculated according to Fig. 3. Current introduces two variables, related to module and phase of the current.

We can write the new power expressions due to current:

$S_i^c = V_i I^*$ $S_j^c = -V_j I^*$ (1)

$P_i^c = V_i I\cos(\varphi - \theta_i)$ $P_j^c = -V_j I\cos(\varphi - \theta_j)$ (2)

$Q_i^c = V_i I\sin(\varphi - \theta_i)$ $Q_j^c = -V_j I\sin(\varphi - \theta_j)$ (3)

We have

$P_i = P_i^0 + P_i^c$ $P_j = P_j^c$ (4)

$Q_i = Q_i^0 + Q_i^c$ $Q_j = Q_j^c$ (5)

Placing the new variables and at and position, respectively, the new vector of variables can be written

$[x^t] = [\theta_1\ ,\theta_2, .\ \theta_{n-1,}\varphi, V_1, V_2, \dots V_{n-1}, I]$ (6)

B. Series Voltage Equations

The following treatment of the series voltages for the UPFC is general for FACTS devices that can employ this feature. The main example is the SSSC and, as a consequence, other apparatus such as IPFC and GIPFC that use series voltage can be modeled as well. Writing the voltage equation between nodes and we obtain

$V_j - V_i = V_s$

The series voltage will be treated similarly to the PIM model of:

$V_s = rv_i e^{j\delta}$ (8)

Where r is the factor for series voltage and is the series voltage angle.That equation substituted in (7) results

$\bar{v}_j - \left(1 + re^{j\delta}\right)\bar{v}_i = 0$ (9)

If r and δ are constants, in a regular powerflow case, calling the complex variable

$A\angle\alpha = -(1 + r\angle\delta)$ (10)

$\bar{v}_j + A\angle\alpha\,\bar{v}_i = 0$ (11)

We obtain the equations, relative to the real and imaginary parts and, respectively:

$F_n = AV_i\cos(\alpha + \theta_i) + V_j\cos\theta_j$ (12)

$G_n = AV_i\sin(\alpha + \theta_i) + V_j\sin\theta_j$

These equations will be put at the end of the equation system. If r and del are variables in an escalation case, we have

$[x^t] = [\theta_1\ ,\theta_2, \dots \theta_{n-1,}\varphi, \delta, V_1, V_2, \dots \dots V_{n-1}, I, r]$

$F_n = V_j\cos(\theta_j) - V_i[\cos(\theta_i) + \cos(\theta_i + \delta)]$ (15)

$G_n = V_j\sin(\theta_i) - V_i[\sin(\theta_i) + \sin(\theta_i + \delta)]$

C. Power Balance

In order to complete the UPFC model, it is necessary to introduce the power balance equation between series and shunt converters. The series power will be added to the shunt power of busbar, similarly (see Fig. 4).

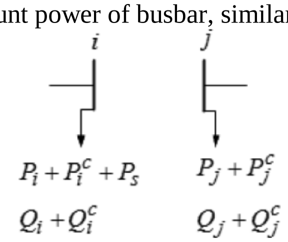

Fig4: Injected powers in the busbars with the inclusion of UPFC.

Let us calculate the power in the series converter:

$S^s = re^{j\delta}V_i I\angle - \varphi)$

Splitting the previous expression in active and reactive powers:

$P^s = rV_i I\cos(\theta_i + \delta - \varphi)$ (18)

$Q^s = rV_i I\sin(\theta_i + \delta - \varphi)$ (19)

D. Complete Jacobian

Calling the Jacobian matrix, without UPFC power addition

$$J_c^0 = \begin{bmatrix} H^0 & N^0 \\ J^0 & L^0 \end{bmatrix} \quad (20)$$

Let us add the injected power due to current in busbars and also the voltage equations. The additional correction of the Jacobian matrix, due to the power balance equation, is also included, complementing the formulation

$$[J] = [J_c^0] + [J^c] + [J^s] \quad (21)$$

The elements of the Jacobian matrix are offered in Appendix A.

***E.* Quasi-Newton optimization approach**

The behavior of the schemed model was studied with an escalation power flow code based on the Quasi-Newton method. The Quasi-Newton method was used in order to compare time answers of PIM and CBM models, adopting the same initial conditions and trying to obtain similar results as possible, although some differences in the equations of both cases can lead to small discrepancies in some variables of the system. The approximation formula used in the Quasi-Newton method is given by [12] and [14]

$$E_{k+1} = \left[I_d - \frac{p_k y_k^T}{p_k^T y_k}\right] E_k \left[I_d - \frac{y_k^T p_k}{p_k^T y_k}\right] + \frac{p_k p_k^T}{p_k^T y_k} \quad (22)$$

Where

E_{k+1}=inverse of approximation of Taylor series expansion of the gradients of f in x_{k+1}

$p_k = E_k + j y_k$ secant relationship or Quasi Newton

Y_k = Taylor series expansion ($\nabla f\, x_{k+1}$-$\nabla f x_k$)

I_d = Identity matrix

Current restrictions are introduced in the formulation. In the CBM, current module and angle are the variables of the problem, while for PIM current equation is introduced according to

$$\bar{I} = \left(V_i \angle\theta_i + r V_i \angle(\theta_i + \delta) - V_j \angle\theta_j\right)(j b_s) \quad (23)$$

Equation (23) would be a little more complex if the series admittance was not simplified to disregarding series impedance losses.

III. CURRENT BASED MODEL OF DG

When we place UPFC in the network still we have losses to reduce these and to improve the voltage profile distributed generation (DG) is placed. Depending upon the voltage constraints the dg location is founded i.e, The voltage at the node exceeds the maximum voltage, at that particular node DG is placed. After DG placement Voltage Profile is improved and power losses are reduced. The load flow studies are done through current based model only but for good results and power quality improvement we introducing the DG's.

IV. RESULTS

Several comparative tests performed with CBM and PIM models offered identical results in power flow analysis using a Matlab code. An additional comparison with the model of was made, using the Power World program.

Some modifications in the New England System of 39 bus-bars were introduced with the purpose of highlighting the optimization results. Generator 2 is the swing busbar, and the other generators are considered power variable generators and generation costs are also offered. In the modified network, the base case does not converge and convergence can only be attained if the power generation cost is optimized. If current restrictions are used in some lines, convergence is only attained with UPFCs in the network.

Voltage results were considered inside the range 0.95 to 1.05 pu for network busbars. In order to make a fair comparison

By the UPFC the power losses are considerably high so for reducing the power losses introducing the DGs to this network. For the allocation of DG here we are considering the voltage constrains and losses are consider for the size of the DG the improved performance is also presented for both 3 upfc model and 6 upfc models.

A. Network with 3 UPFCs

With 3 UPFCs, despite the higher Jacobian dimension of CBM, its convergence time is lower since restrictions on current treated as a variable enable fast convergence. Most variables such as voltage, current and angle obtained in the convergence of three UPFCs are identical in both models, but this is not true if current limits are increased. Reducing the current band limits, PIM does not usually converge. The same generation cost offered by the two models and the lower computation time of the CBM model can be verified this is presented in table I.

TABLE I

	PIM	CBM	Difference
Cost.gen.	657.762	657.761	0.000289
Time(sec)	100	80	20

With 3 UPFCs, despite the higher Jacobian dimension of CBM, its convergence time is lower since restrictions on current treated as a variable enable fast convergence. Most variables such as voltage, current and angle obtained in the convergence of three UPFCs are identical in both models, but this is not true if current limits are increased. Reducing the current band limits, PIM does not usually converge.

Before placement of DG the active and reactive power losses are 16.552Mw 83.125Mvar.After placement of DG the losses are reduced to 1.395Mw and 25.260 Mvar respectively. The bus wise losses without and with DG placement are shown in fig.5 and fig.6 respectively.

TABLE II

	With UPFC only	With UPFC and DG
Active power loss(MW)	16.552	1.395
Reactive power loss(MW)	83.125	25.260

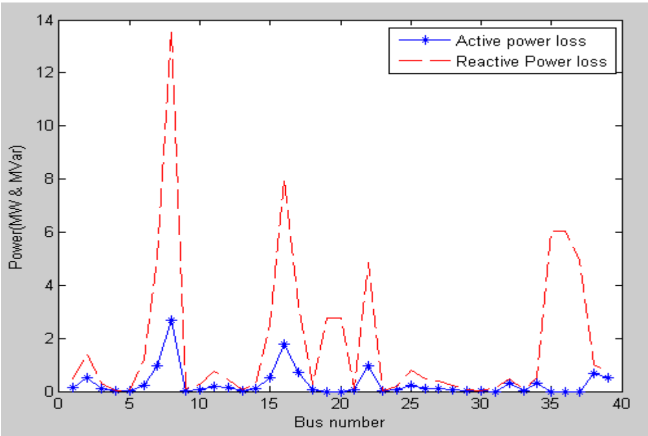

Fig.5. power losses without DG placement

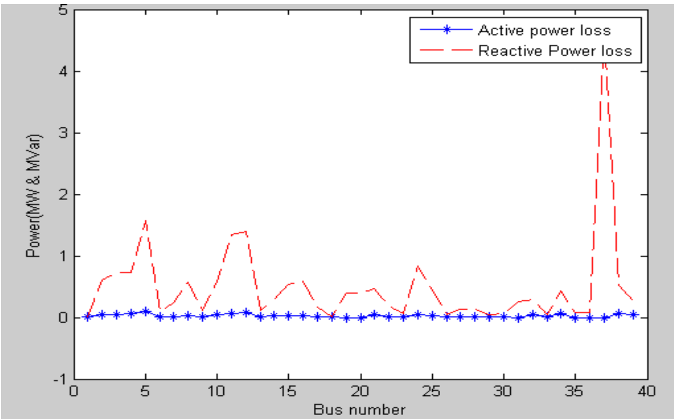

Fig.6. power losses with DG placement

B. Network with 6 UPFCs

By increasing the number of UPFCs to 6, the lower convergence time of CBM is still more evident. The results of the variables of the two models are not similar but generation costs are almost the same for these limits. If the limits are increased, different generation costs can be yielded for the models.the cost generation with two models are shown in tabel II.

TABLE III

	PIM	CBM	Difference
Cost.gen.	518.649	518.631	0.003
Time(sec)	100	80	20

In several cases, it was observed that for all the set of current limits that allow convergence for the PIM models also leads the CBM model to convergence. On the other hand, the inverse is not true, with CBM presenting a better functioning in cases of difficult convergence due to current restrictions, mainly in cases with narrower current limits.

With the 6 upfcs Before placement of DG the active and reactive power losses are 16.552Mw and 83.125 Mvar After placement of DG the losses are reduced to 1. .405Mw and 25.576 Mvar. The bus wise losses without and with DG placement are shown in fig.7 and fig.8 respectively

TABLE IV

	With UPFC only	With UPFC and DG
Active power loss(MW)	16.552	1.405
Reactive power loss(MW)	83.125	25.576

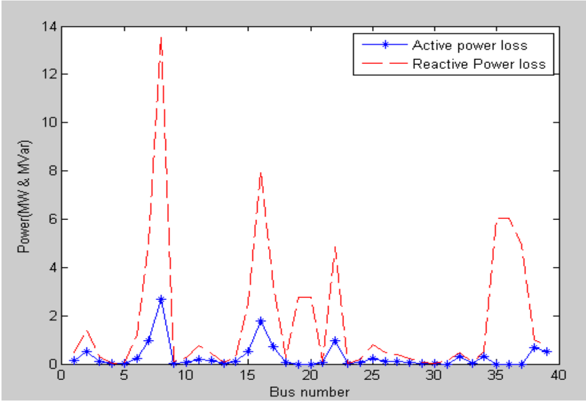

Fig.7. power losses without DG placement

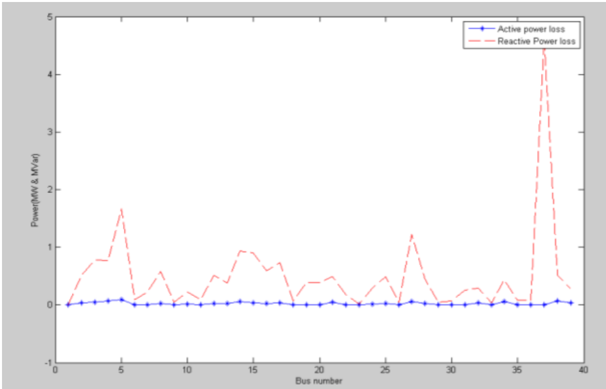

Fig.8. power losses with DG placement

IV. CONCLUSION

The suggestion of an substitute formulation for the modeling of UPFC was offered, considering the current in the series converter as a variable. The schemed CBM model was compared with the conventional power injection model PIM, showing coincident results in power flow evaluations.

In Quasi Newton Optimization approach, despite carrying out with two additional equations for each UPFC, the CBM model reduces the computational time, when current restrictions are introduced in the series converters, mainly when dealing with several UPFC in the system, which is a very important issue in FACTS design.

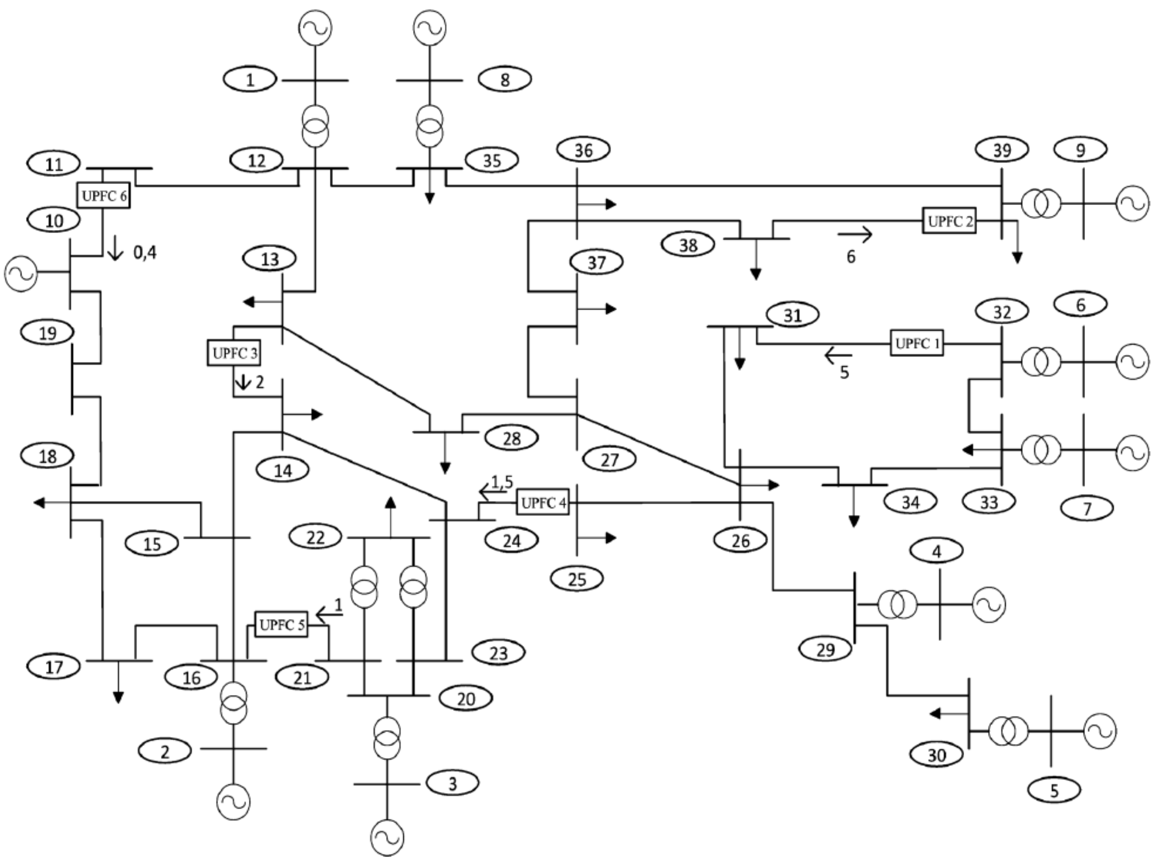

Fig.9 Modified England network with 6 UPFC

Distributed generations (DGs) are placed to minimize the total power loss of system. Depending on the voltage constraints the dg location is founded. The load flow studies are done through current based model only but for good results and power quality improvement

APPENDIX A

The Cost function is given by $a_{2i}(P_i)^2 + a_{1i}(P_i) + a_0$
The values of a_2, a_1, a_0 are given in the following table

Node	Value of the generation cost		
	A_2	A_1	A_0
1	1	10	0
2	1	10	0
3	1.5	15	0
4	0.5	5	0
5	0.4	4	0
6	0.6	6	0
7	0.7	7	0
8	1	10	0
9	0.3	3	0
10	1	10	0

Correction terms of the jacobian matrix due to injection current when r and δ are constants

H terms :

$H_{ii}^c = \frac{\partial P_i^c}{\partial \theta_i} = -Q_i^c \qquad H_{jj}^c = \frac{\partial P_j^c}{\partial \theta_j} = -Q_j^c$

$H_{in}^c = \frac{\partial P_i^c}{\partial \varphi} = -Q_i^c \qquad H_{jn}^c = \frac{\partial P_j^c}{\partial \varphi} = -Q_j^c$

$H_{ni} = -AV_i \sin(\alpha + \theta_i) \quad H_{nj} = -V_j \sin(\theta_j)$

N terms:

$N_{ii}^c = V_i \frac{\partial P_i^c}{\partial V_i} = P_i^c \qquad N_{jj}^c = V_j \frac{\partial P_j^c}{\partial V_j} = P_j^c$

$N_{in}^c = I \frac{\partial P_i^c}{\partial I} = P_i^c \qquad N_{nj}^c = I \frac{\partial P_i^c}{\partial \varphi} = P_j^c$

$N_{ni} = AV_i \cos(\alpha + \theta_i) \quad N_{nj} = V_j \cos(\theta_j)$

J terms:

$J_{ii}^c = \frac{\partial Q_i^c}{\partial \theta_i} = P_i^c \qquad J_{jj}^c = \frac{\partial Q_j^c}{\partial \theta_j} = P_j^c$

$J_{in}^c = \frac{\partial Q_i^c}{\partial \varphi} = -P_i^c \qquad J_{jn}^c = \frac{\partial Q_j^c}{\partial \varphi} = -P_j^c$

$J_{ni} = AV_i \cos(\alpha + \theta_i) \quad J_{nj} = V_j \cos(\theta_i)$

L terms:

$L_{ii}^c = V_i \frac{\partial Q_i^c}{\partial \theta_i} = Q_i^c \qquad L_{jj}^c = V_j \frac{\partial Q_j^c}{\partial \theta_j} = Q_j^c$

$L_{in}^c = I \frac{\partial Q_i^c}{\partial I} = Q_i^c \qquad L_{in}^c = I \frac{\partial Q_j^c}{\partial \varphi} = Q_j^c$

$L_{ni} = AV_i \sin(\alpha + \theta_i) \quad L_{nj} = V_j \sin(\theta_j)$

Correction in Jacobian terms due to power balance

H trems:

$H_{ii}^s = \frac{\partial P_s}{\partial \theta_i} = -rV_i \sin(\theta_i + \delta - \varphi) = -Q^s$

$H_{in}^s = \frac{\partial P_s}{\partial \varphi} = rV_i \sin(\theta_i + \delta - \varphi) = Q^s$

N terms:

$N_{ii}^s = V_i \frac{\partial P_s}{\partial V_i} = rV_i I \cos(\theta_i + \delta - \varphi) = P_s$

$N_{in}^s = I \frac{\partial P_s}{\partial I} = rV_i I \cos(\theta_i + \delta - \varphi) = P_s$

[H] sub –matrix terms

$H_{ii} = H_{ii}^0 - Q_i^c - Q^s \qquad H_{jj} = H_j^0 - Q_j^c$

$H_{in} = Q_i^c + Q^s \qquad H_{jn} = Q_j^c$

$H_{ni} = -AV_i \sin(\alpha + \theta_i) \quad N_{nj} = -V_j \sin(\theta_j)$

[N] sub matrix terms

$N_{ii} = N_{ii}^0 + P_c^i + P^s \qquad N_{jj} = N_{jj}^0 + P_j^c$

$N_{in} = P_i^c + P^s \qquad N_{jn} = P_j^c$

$N_{ni} = AV_i \cos(\alpha + \theta_i) \quad N_{nj} = V_j \cos \theta_j$

[J] Sub matrix terms

$J_{ii} = P_i^0 + P_i^c \quad J_{jj} = J_{jj}^0 + P_j^c$

$J_{in} = -P_i^c \qquad J_{jn} = -P_j^c$

$J_{ni} = AV_i \cos(\alpha + \theta_i) \quad J_{nj} = V_j \cos \theta_j$

[L] Sub matrix terms

$L_{ii} = L_{ii}^0 + Q_i^c \qquad L_{jj} = L_{jj}^0 + Q_j^c$

$L_{in} = Q_i^c \qquad L_{jn} = Q_j^c$

$L_{ni} = AV_j \sin(\alpha + \theta_j) \quad L_{nj} = V_j \sin(\theta_j)$

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