Tap Adjustment in AC Load Flow

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September, 2002

Transformers

Transformers are used to transfer power between different voltage levels or to regulate real or reactive flow through a particular transmission corridor. Most transformers come equipped with taps on the windings to adjust either the voltage transformation or the reactive flow through the transformer. Such transformers are called either load-tap-changing (LTC) transformers or on load tap-changing (OLTC) transformers.

Another type of transformer is known as a phase-shifting transformer (or phase shifter). Phase-shifting transformers, which are less common than LTC transformers, vary the angle of the phase shift across the transformer in order to control the MW power flow through the transformer. This type of control can be very useful in controlling the flow of real power through a transmission system.

The emphasis of this document is the modelling of different types of transformers in AC load flow. The first section is a short introduction in different types of transformer considered in such AC load flow, afterwards a comprehensive branch model and the expressions for line flows trough transformer are given. The summary of the previous work based on several references was given in the section Review of the Previous work. The succeeding sections contain the basic ideas, formulations, adjustment interactions and algorithm for tap adjustments based on AC sensitivity analysis. Small examples are given in the last two sections for the sake of practicality.

Off-nominal Turns Ratio and Phase Shift Degrees

The off-nominal tap ratio determines the additional transformation relative to the nominal transformation. This value normally ranges from 0.9 to 1.1 (1.0 corresponds to no additional transformation). For phase-shifting transformers the phase shift value normally ranges from about -40° to 40°.

Several types of transformers are considered:
1)No Automatic Control (taps are assumed fixed),
2) Automatic Voltage Regulation (AVR),
3) Reactive Power Control, and
4) Phase Shift Control.

Transformers with fixed taps operate at the given off-nominal turns ratio and phase shift, and will remain fixed at those values during the entire power flow solution process unless manually changed by the user.

When on automatic voltage control, the transformer taps automatically change to keep the voltage at the regulated bus (usually one of the terminal buses of the transformer) within a voltage range between the minimum voltage and maximum voltage values.

When on automatic reactive power control, the transformer taps automatically change to keep the reactive power flow through the transformer (measured at the from bus) within a user-specified range.

When a transformer is on phase shift control, the transformer phase shift angle automatically changes to keep the MW flow through the transformer (measured at the regulated bus end) between the minimum and maximum flow values (with flow into the transformer assumed positive).

A Comprehensive Branch Model for Transformers

Figure 1. shows the basic equivalent circuit of transformer in respect to the complex current ($\boldsymbol{I}_i, \boldsymbol{I}_i^{'}, \boldsymbol{I}_j$), complex voltages ($\boldsymbol{V}_i, \boldsymbol{V}_i^{'}, \boldsymbol{V}_j$), complex tap ratio ($\boldsymbol{t}$) and admittance $\boldsymbol{y}$.

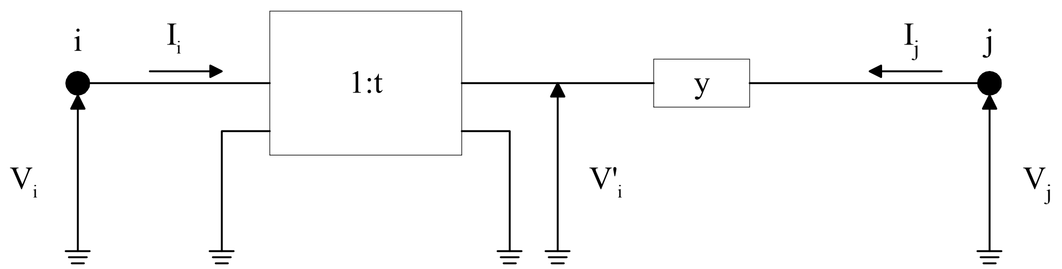

Figure 1. Transformer equivalent circuit

The voltage and current ratio can be then defined as follows:

$$\boldsymbol{V}_i : \boldsymbol{V}_i^{'} = 1 : \boldsymbol{t} \ \ and \ \ \boldsymbol{I}_i : \boldsymbol{I}_i^{'} = \boldsymbol{t}^* : 1 \ \ due\,to \ \ \boldsymbol{V}_i^* \boldsymbol{I}_i = \boldsymbol{V}_i^{'*} \boldsymbol{I}_i^{'} \qquad \text{(T1)}$$

where:

- * -refers to conjugate complex number
- $\boldsymbol{V}_i$ -is the complex voltage at the *i* end of the line *i-j*,
- $\boldsymbol{V}_i^{'}$ -is the complex voltage behind the ideal transformer,
- $\boldsymbol{V}_j$ -is the complex voltage at the *j* end of the line *i-j*,
- $\boldsymbol{I}_i$ -is the complex current at the *i* end of the line *i-j*,
- $\boldsymbol{I}_i^{'}$ -is the complex current behind the ideal transformer,
- $\boldsymbol{I}_j$ -is the complex current at the *j* end of the line *i-j*,
- $\boldsymbol{t}$ -refers to the complex tap ratio of the transformer.

The transformer equivalent circuit shown in Fig. 1. can be transformed to an equivalent π circuit using the following equations:

$$\boldsymbol{I}_i = \boldsymbol{t}^* \boldsymbol{I}_i^{'} = \boldsymbol{t}^* (\boldsymbol{V}_i^{'} - \boldsymbol{V}_j)\boldsymbol{y} = \boldsymbol{t}^* (\boldsymbol{t}\boldsymbol{V}_i - \boldsymbol{V}_j)\boldsymbol{y} = t^2 \boldsymbol{V}_i \boldsymbol{y} - \boldsymbol{t}^* \boldsymbol{V}_j \boldsymbol{y},$$

$$\boldsymbol{I}_j = (\boldsymbol{V}_j - \boldsymbol{V}_i^{'})\boldsymbol{y} = (\boldsymbol{V}_j - \boldsymbol{t}\boldsymbol{V}_i)\boldsymbol{y} = -\boldsymbol{t}\boldsymbol{V}_i \boldsymbol{y} + \boldsymbol{V}_j \boldsymbol{y},$$

or in a matrix form:

$$\begin{bmatrix} \boldsymbol{I}_i \\ \boldsymbol{I}_j \end{bmatrix} = \begin{bmatrix} t^2 \boldsymbol{y} & -\boldsymbol{t}^* \boldsymbol{y} \\ -\boldsymbol{t}\boldsymbol{y} & \boldsymbol{y} \end{bmatrix} \begin{bmatrix} \boldsymbol{V}_i \\ \boldsymbol{V}_{\mathrm{j}} \end{bmatrix} \tag{T2}$$

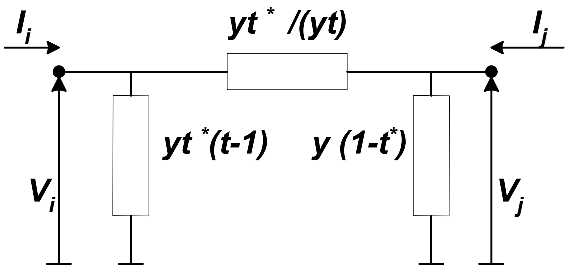

Figure 2. Comprehensive branch model for8 transformers

Based on equation (T2) a comprehensive branch model is shown in Fig. 2. It should be noted that only phase shifter transformer has $\boldsymbol{y}_{ij} \neq \boldsymbol{y}_{ji}$, while for all others types of transformer $\boldsymbol{t}^* = \boldsymbol{t}$ and consequently $\boldsymbol{y}_{ij} = \boldsymbol{y}_{ji}$. Besides, this branch model assumes that the transformer admittance is behind the off nominal side of transformer. Some other branch models are given in [1].

Line Flows Through A Transformer

The complex line flow from node *i* to node *j* can be formulated as:

$$\boldsymbol{S}_{ij} = \boldsymbol{V}_i^* \{\boldsymbol{y}\boldsymbol{t}^* (\boldsymbol{t} - 1)\boldsymbol{V}_i + (\boldsymbol{V}_i - \boldsymbol{V}_j)\boldsymbol{y}\boldsymbol{t}^*\} = V_i^2 t^2 \boldsymbol{y} - V_i^2 \boldsymbol{t}^* \boldsymbol{y} + V_i^2 \boldsymbol{t}^* \boldsymbol{y} - \boldsymbol{V}_i^* \boldsymbol{V}_j \boldsymbol{t}^* \boldsymbol{y},$$

$$\boldsymbol{S}_{ij} = V_i^2 t^2 \boldsymbol{y} - \boldsymbol{V}_i^* \boldsymbol{V}_j \boldsymbol{t}^* \boldsymbol{y}, \tag{T3}$$

Using polar coordinates the voltages, tap ratio and admittance can be written as follows:

- $\boldsymbol{V}_i = V_i e^{j\theta_i}, V_i = \|\boldsymbol{V}_i\|, \theta_i = \angle \boldsymbol{V}_i,$ (T4)
- $\boldsymbol{V}_j = V_j e^{j\theta_j}, V_j = \|\boldsymbol{V}_j\|, \theta_j = \angle \boldsymbol{V}_j,$ (T5)

- $\boldsymbol{t} = \mathrm{t}e^{\boldsymbol{j}\theta}, \mathrm{t} = \|\boldsymbol{t}\|, \theta = \angle \boldsymbol{t}$ (T6)
- $\boldsymbol{y} = \mathrm{y}e^{\boldsymbol{j}\psi} = \mathrm{g} + \boldsymbol{j}\mathrm{b}, \psi = \arctan\frac{\mathrm{b}}{\mathrm{g}}$ (T7)

Substituting the complex variables with the polar coordinates given in equations (T4-T7), equation (T3) can be rewritten as:

$$\boldsymbol{S}_{ij} = V_i^2 t^2 (g + \boldsymbol{j}b) - V_i\, V_j t y e^{-\boldsymbol{j}(\theta_i - \theta_j - \psi + \theta)}) , \tag{T8}$$

or, in terms of real and reactive power flows as:

$$P_{ij} = \mathrm{Re}\{S_{ij}\} = \{V_i^2 t^2 g - V_i V_j t y \cos(\theta_i - \theta_j - \psi + \theta)\}, \tag{T9}$$

$$Q_{ij} = -\mathrm{Im}\{S_{ij}\} = \{-V_i^2 t^2 b - V_i V_j t y \sin(\theta_i - \theta_j - \psi + \theta)\}. \tag{T10}$$

Similarly one can calculate the line flows in the opposite direction (from j to i):

$$\boldsymbol{S}_{ji} = \boldsymbol{V}_j^* \{\boldsymbol{y}(1 - \boldsymbol{t})\boldsymbol{V}_j + (\boldsymbol{V}_j - \boldsymbol{V}_i)\boldsymbol{y}\boldsymbol{t}\} = V_j^2 \boldsymbol{y} - V_j^2 \boldsymbol{t}\boldsymbol{y} + V_j^2 \boldsymbol{t}\boldsymbol{y} - \boldsymbol{V}_j^* \boldsymbol{V}_i \boldsymbol{t}\boldsymbol{y} ,$$

$$\boldsymbol{S}_{ji} = V_j^2 \boldsymbol{y} - \boldsymbol{V}_j^* \boldsymbol{V}_i \boldsymbol{t}\boldsymbol{y} \tag{T11}$$

or, in terms of real and reactive power as:

$$P_{ji} = \mathrm{Re}\{S_{ji}\} = \{V_j^2 g - V_i V_j t y \cos(\theta_j - \theta_i - \psi - \theta)\}, \tag{T12}$$

$$Q_{ji} = -\mathrm{Im}\{S_{ji}\} = \{-V_j^2 b - V_i V_j t y \sin(\theta_j - \theta_i - \psi - \theta)\}. \tag{T13}$$

Review of the Previous Work

Several approaches to automatic tap adjustment have been found in the literature [2-5]. These can be categorised as follows:

- Tap changer value is modelled as an independent variable instead of the controlled voltage [2,5]. When the tap changer hits the limit, it must be fixed and replaced by the controlled voltage in the state vector (vector of independent variables).
- The controlled voltage is a state variable all the time [3-4]. When the controlled voltage is not within the specified limit, the corresponding tap changer will move in order to bring the voltage to the specified range.

The previous modelling of tap changer in the Newton-Raphson (N-R) iteration procedure was based on an approach from the first category. It was shown by some researchers at UMIST that this approach has serious problems to handle tap limits. In a Newton - Raphson iteration procedure, tap adjustments might force taps to move beyond their limits. Once a tap hits its limit, it will be fixed and replaced by the controlled voltage in the state variable vector. This replacement will significantly perturb the Jacobian, causing the propagation of perturbation to subsequent iterations, frequently leading the iterative procedure to a solution quite different from the expected one. Therefore, the biggest problem in this so-called bus switching approach is the effect of perturbation caused by the needed replacements in the state vector.

The tap adjustments approaches that belong to the second category are based on the sensitivity calculation [3,4]. The sensitivity (desired) function in such calculation is the controlled variable and the control variable is the corresponding tap changer value. This sensitivity calculation is based on $(\boldsymbol{B}'')^{-1}$ and the second cycle of the fast-decoupled load flow. Fast forward –backward substitutions is used to obtain an auxiliary solution and update the voltages. If there are no interactions between adjustments this approach works reasonable well. Therefore, the emphasis of this document is on the AC sensitivity based adjustments. The novelty of this approach is in using the inverse of the Jacobian matrix to calculate exact sensitivities.

Tap Adjustment Using AC Sensitivity Analysis

The steady state equilibrium conditions for a power network can be represented by a system of N real non-linear network equations:

$$\boldsymbol{g}(\boldsymbol{x}, \boldsymbol{y}) = \boldsymbol{0} \tag{T14}$$

where $\boldsymbol{x}$ is the vector of independent variables (for example active and reactive power at a PQ bus) and $\boldsymbol{y}$ is the vector of dependent variables (for example voltage and angle for a PQ bus). This system of non-linear equations can be linearised at a particular point $\boldsymbol{x}_0$ by expanding it into a Taylor's series and retaining only the first- order terms. Therefore,

$$\frac{\partial \boldsymbol{g}(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p})}{\partial \boldsymbol{x}}\Big|_{\boldsymbol{x}_0} \Delta\boldsymbol{x} = -\frac{\partial \boldsymbol{g}(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p})}{\partial \boldsymbol{u}}\Big|_{\boldsymbol{x}_0} \Delta\boldsymbol{u}\,, \tag{T15}$$

where the vector of independent variables $\boldsymbol{y}$ is split into the vector of controllable variables $\boldsymbol{u}$ (for example tap changer values) and the vector of fixed parameters $\boldsymbol{p}$.

The changes in any desired function $\boldsymbol{f}(\boldsymbol{x},\boldsymbol{y})$ with respect to the single parameter change $\Delta \mathrm{u}_\mathrm{i}$ can be found from the total differential as follows [6]:

$$\Delta f = \frac{\partial f(\boldsymbol{x},\boldsymbol{y})}{\partial \boldsymbol{x}}\Big|_{x_0} \Delta\boldsymbol{x} + \frac{\partial f(\boldsymbol{x},\boldsymbol{y})}{\partial \boldsymbol{u}}\Big|_{x_0} \Delta\boldsymbol{y}$$

Substituting $\Delta\boldsymbol{x}$ from (T15) into the above equation:

$$\Delta f = -\frac{\partial f(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p})}{\partial \boldsymbol{x}}\Big|_{x_0}\left[\frac{\partial \boldsymbol{g}(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p})}{\partial \boldsymbol{x}}\Big|_{x_0}\right]^{-1}\frac{\partial \boldsymbol{g}(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p})}{\partial u_i}\Big|_{x_0}\Delta u_i + \frac{\partial f(\boldsymbol{x},\boldsymbol{u},\boldsymbol{p})}{\partial u_i}\Big|_{x_0}\Delta u_i$$

$$\frac{\Delta f}{\Delta u_i} = -\frac{\partial f}{\partial \boldsymbol{x}}\Big|_{x_0}\boldsymbol{J}^{-1}\Big|_{x_0}\frac{\partial \boldsymbol{g}}{\partial u_i}\Big|_{x_0} + \frac{\partial f}{\partial u_i}\Big|_{x_0} \tag{T16}$$

Using equation (T16) the change of control variable $\Delta \mathrm{u}_\mathrm{i}$ can be adjusted to achievestrike the desired change in function $\boldsymbol{f}$ if the sensitivity value $\frac{\Delta f}{\Delta u_i}$ is known. This sensitivity analysis with respect to a single parameter change can be implemented in tap adjustments, selecting appropriate desired functions. Thus, in the case of the voltage-controlled transformers the desired function is the voltage at the controlled bus. For reactive power control transformers the desired function is the reactive power flow at the from bus. In both cases, the controllable variable $\Delta \mathrm{u}_\mathrm{i}$ is the tap changer value. The calculation of sensitivity shown in the previous equation requires the following calculation steps:

1. calculation of $\frac{\partial f}{\partial \boldsymbol{x}}$,
2. calculation of $\boldsymbol{J}^{-1}$
3. calculation of $\frac{\Delta \boldsymbol{g}}{\partial u_i}$ and
4. calculation of $\frac{\partial f}{\partial u_i}$.

The calculation of $\frac{\partial f}{\partial \boldsymbol{x}}$ and $\frac{\partial f}{\partial u_i}$ depends on the desired function choice as it will be shown separately for both type of transformers in the following sections.

The calculation of $\frac{\partial f}{\partial \boldsymbol{x}}, \frac{\partial \boldsymbol{g}}{\partial u_i}$ and $\frac{\partial f}{\partial u_i}$ in the case where the voltage control transformer between the buses *i* and *j* is used to control the voltage at bus *j* within a specified range. Therefore, the desired function is $f = V_j$ and the control variable is $u_i = t_{ij}$. Then, the calculation required by the steps 1,3, and 4 (see the previous section) is:

- $\frac{\partial f}{\partial \boldsymbol{x}} = \begin{bmatrix} 0 & 0 & \cdots & 1 & 0 \end{bmatrix} = \boldsymbol{e}_j^T$, where the non-zero entry refers to the position of the voltage V_j in the state vector (vector of independent variables) of the Newton-Raphson iteration procedure.
- $$\frac{\Delta \boldsymbol{g}}{\partial u_i} = \begin{bmatrix} 0 \\ \vdots \\ \frac{\partial PB_i}{\partial t} \\ \frac{\partial PB_j}{\partial t} \\ 0 \\ \vdots \\ \frac{\partial QB_i}{\partial t} \\ \frac{\partial QB_j}{\partial t} \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ -2tV_i^2 g + V_i V_j |y| \cos(\theta_i - \theta_j - \psi\ ) \\ V_i V_j |y| \cos(\theta_j - \theta_i - \psi) \\ 0 \\ \vdots \\ 2tV_i^2 b + V_i V_j |y| \sin(\theta_i - \theta_j - \psi) \\ V_i V_j |y| \sin(\theta_j - \theta_i - \psi) \\ \vdots \\ 0 \end{bmatrix}, \qquad \text{(T17)}$$

  where $PB_i, PB_{j,} QB_i, QB_j$ are the real and reactive balance equation at buses *i* and *j*, respectively. These balance equations give the total injection of real and reactive power into a bus, summing generation, load and line flows to/from the bus ($PB_{i/j} = P_{i/j}^G - P_{i/j}^L - P_{i/j}^{inj}$ and $QB_{i/j} = Q_{i/j}^G - Q_{i/j}^L - Q_{i/j}^{inj}$). It can be observed that the vector $\frac{\Delta \boldsymbol{g}}{\partial u_i}$ has four non-zero entries.
- $\frac{\partial f}{\partial u_i} = 0$

The calculation of the vectors $\frac{\partial f}{\partial \boldsymbol{x}}, \frac{\partial \boldsymbol{g}}{\partial u_i}$ and $\frac{\partial f}{\partial u_i}$ is really straightforward and computationally fast. On the other hand, the calculation of the inverse Jacobian is time demanding, especially for large systems. This calculation can be avoided using the illustration of the $\frac{\partial f}{\partial \boldsymbol{x}}\Big|_{x_0} \boldsymbol{J}^{-1}\Big|_{x_0} \frac{\partial \boldsymbol{g}}{\partial u_i}\Big|_{x_0}$ matrix multiplication structure shown in Fig. 3. It can be seen that such structure has only one non-zero value in the vector $\frac{\partial f}{\partial \boldsymbol{x}}$, which is beneficial in the sense that the calculation of the inverse Jacobian matrix can be avoided. In essence, in Fig.3

we can observe that only one row of the inverse Jacobian matrix is required. If the dimension of the Jacobian matrix is N, than having found the lower ($\boldsymbol{L}$) and the upper ($\boldsymbol{U}$) triangular sub-matrices, an inverse matrix calculation would require N forward-backward substitutions ($\boldsymbol{J} * \boldsymbol{J}^{-1} = \boldsymbol{I} \;\Rightarrow LU * [\boldsymbol{j}_1 \;\; \boldsymbol{j}_2 \;\; \cdots \;\; \boldsymbol{j}_N] = [\boldsymbol{e}_1 \;\; \boldsymbol{e}_2 \;\; \cdots \;\; \boldsymbol{e}_N]$). In each of these substitutions ($\boldsymbol{LU} * \boldsymbol{j}_i = \boldsymbol{e}_i$, $i = 1, N$) one column ($\boldsymbol{j}_i$,) of the inverse Jacobian matrix is determined. However, this time consuming calculation of each column to determine only one row of the inverse Jacobian can be avoided using the equation $(\boldsymbol{J}^{-1})^T = (\boldsymbol{J}^T)^{-1}$. Therefore, instead of N forward-backward substitutions only one substitution ($\boldsymbol{U}^T \boldsymbol{L}^T * \boldsymbol{j}_j^{row} = \boldsymbol{e}_j$) will be required to determine the row $\boldsymbol{j}_j^{row}$ that corresponds to the position of the independent variable $\boldsymbol{V}_j$ (see Figure 3). The next simplification in the sensitivity calculation is related to the LU decomposition. At each iteration step in a Newton-Raphson procedure, LU decomposition is needed. Using the assumption that the change of the Jacobian matrix is not so dramatic between two subsequent steps in a Newton-Rapshon iteration procedure, already obtained $\boldsymbol{L}$ and $\boldsymbol{U}$ sub-matrices can be used for the calculation of the corresponding inverse Jacobian row. This assumption is even more sensible if one takes into account that the tap adjustments will take place only if the maximal mismatch in the iteration procedure is relatively small. A complete algorithm of the suggested tap adjustments is shown in Fig. 4. Special attention is paid to acceleration factors in order to prevent excessive tap movements or to avoid oscillations in the iteration procedure. These oscillations might appear if a tap change of a transformer cause unwanted change of another voltage controlled by another transformer. These adjustment interactions are summarised in [7], which is in the author's opinion is the best paper ever written on this topic. Therefore, the effect of a tap change can be sometime mitigated/aggravated by another tap change. The acceleration factors are equal to 1.0 if the normal tap change is required, and less than 1.0 for excessive tap changes. It should be noted that the impact of simultaneous tap adjustments on divergence has not been fully investigated. However, the testing has shown that a correct choice of the acceleration factors makes this algorithm very robust in terms of convergence. The tap adjustments based on this approach have been successfully tested on IEEE 14 bus system and the NGC power system (1100 buses, 1700 branches). An illustrative example is given at the end of this document, emphasising some crucial points of the suggested AC sensitivity approach.

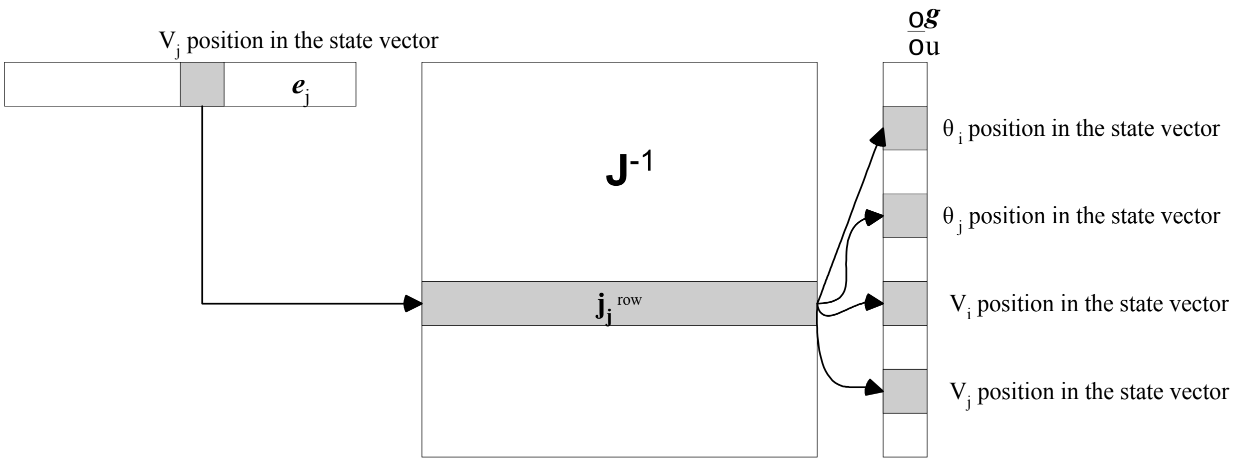

Figure 3 – Illustration of non-zero entries used for sensitivity calculation

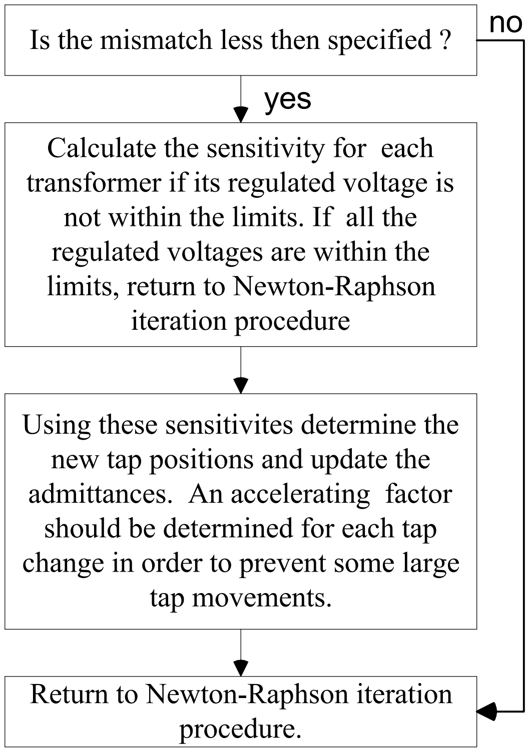

Figure 4 – Algorithm of tap adjustments

Tap Adjustments of Reactive Power Control Transformers Based On Sensitivity Analysis.

Reactive power control transformers change taps automatically to keep the reactive power flow through the transformer (measured at the from bus) within a user-specified range. Therefore, the desired function and the control variable are $f = Q_{ij}$ and $u_i = t_{ij}$, respectively. The expressions for $\frac{\partial f}{\partial \boldsymbol{x}}$ and $\frac{\partial f}{\partial u_i}$ can be obtained using equation (T11) as follows:

- $$\frac{\Delta f}{\partial \boldsymbol{x}} = \begin{bmatrix} 0 \\ \vdots \\ \frac{\partial Q_{ij}}{\partial \theta_i} \\ \frac{\partial Q_{ij}}{\partial \theta_j} \\ \vdots \\ 0 \\ \frac{\partial Q_{ij}}{\partial V_i} \\ \frac{\partial Q_{ij}}{\partial V_j} \\ \vdots \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ \vdots \\ -V_iV_jt|y|\cos(\theta_i - \theta_j - \psi\ ) \\ V_iV_jt|y|\cos(\theta_i - \theta_j - \psi) \\ \vdots \\ 0 \\ -2V_it^2b - V_jt|y|\sin(\theta_i - \theta_j - \psi) \\ -V_it|y|\sin(\theta_i - \theta j - \psi) \\ \vdots \\ 0 \end{bmatrix}^T \tag{T18}$$

- $$\frac{\partial f}{\partial u_i} = \frac{\partial Q_{ij}}{\partial t_{ij}} = -2V_i^2tb - V_iV_j|y|\sin(\theta_i - \theta_j - \psi) \tag{T19}$$

There are a few changes with respect to the voltage control transformer sensitivity calculation. The vector $\frac{\partial f}{\partial \boldsymbol{x}}$ has now four non-zero entries, and consequently the calculation of four rows of the inverse Jacobian is required. The relatively complex matrix multiplication structure of $\frac{\partial f}{\partial \boldsymbol{x}}\Big|_{x_0} \boldsymbol{J}^{-1}\Big|_{x_0} \frac{\partial \boldsymbol{g}}{\partial u_i}\Big|_{x_0}$ is shown in Fig. 6. The scalar value $\frac{\partial f}{\partial u_i}$ is now a non-zero value.

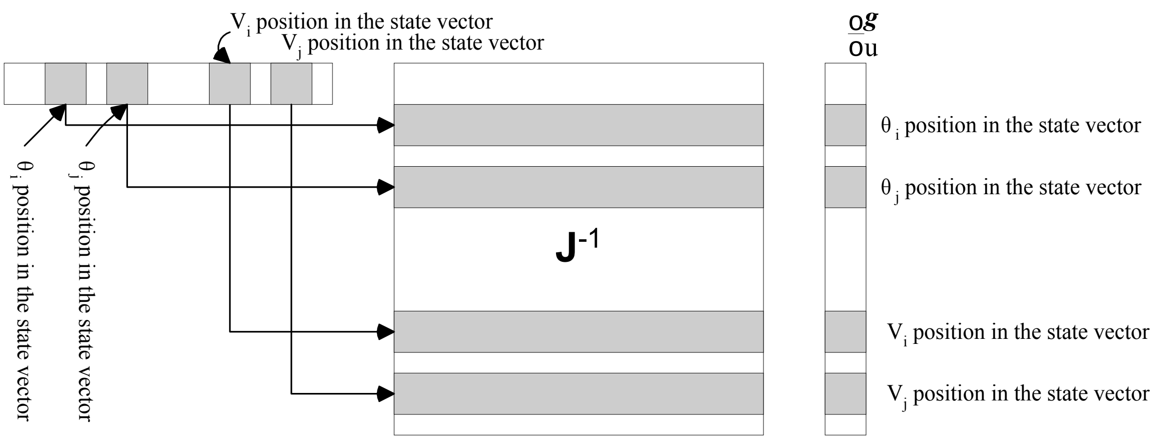

Figure 6 – Illustration of non-zero entries used for sensitivity calculation

Tap Adjustment Interactions

Tap adjustment interactions arise in many different forms in the load flow solution [7]. They slow down the convergence and can often cause oscillatory solution or even divergence. In the past, their existence was accepted as a matter of fact and almost negligible attention has been paid to this problem. Reference [7] is actually one of the rare successful attempts, to tackle this problem. In general, there are three types of interactions [7]. The first one, namely cross-type interactions are the interactions which occur between different types of adjustments, for example generator and its step up transformer controlling the same bus voltage. The single type local interactions occur when a system quantity is simultaneously controlled by multiple devices of the same type, for example two voltage control transformers controlling the same remote voltage. The third one called single type global interactions represent the coupling effects amongst the same type of control devices that regulate different quantities. For example, two voltage control transformers regulate voltage at different PQ buses, which are not directly coupled.

The first type of interactions is handled using the proper starting criteria (mismatch less then a specified small value) and a specific priority. Thus, if a voltage is controlled by generator and a voltage control transformer, the priority will be given to the generator and taken over by the transformer only if the generator hits its Q limits.

The second type of interactions is not considered because the remote voltage control is not considered in the Newton-Raphson iteration procedure.

The third ones are resolved by using an adaptive tracking approach to change acceleration factors [7]. These types of interactions require further testing to make sure that the approach is really robust, as it has been proved on the tested examples. If some further testing show that handling the interactions on this way is not robust enough, than the automatic scaling technique and two- pass solution suggested in [7] can take place.

Novelty and Further Work

This approach deals with reasonable fast calculation of tap adjustment based on the exact sensitivity calculation for a full AC load flow. Tap adjustments can be started only when the solution is moderately converged. An adaptive tracking acceleration factor has been proposed to prevent adjustment interactions.

The author would suggest further improvement especially on:

- interactions adjustment,
- faster calculation of AC sensitivities, and

- the comparison of this approach with the approaches suggested in [2,3,4,7].

Tap Adjustment of Voltage Control Transformer on A Small Example

The given tap adjustments approach was first tested on a small power system shown in Fig.5. The input data related to buses and lines are given in Table 1 and Table 2, respectively.

Table 1 – Bus data

	Type of bus	P load(MW)	Q load(MW)	P gen (MW)	Q gen (MW)
1.Gen_bus	Slack	0.0	0.0	105	104
2.Load_1	PQ	95	43	0.0	0.0
3.Load_2	PQ	55	45	0.0	0.0

Table 2 – Transformer data

ID 1	ID 2	Automatic control	Control value	Lower Limit (control value)	Upper Limit (control value)	Lower tap limit	Upper tap limit
1	2	fixed tap	n.a.	n.a.	n.a.	n.a.	n.a.
1	3	fixed tap	n.a.	n.a.	n.a.	n.a.	n.a.
3	2	Yes	voltage at bus 3 or 2	$0.96_{(3)}$ $0.98_{(2)}$	$0.98_{(3)}$ $0.985_{(2)}$	0.9	1.3

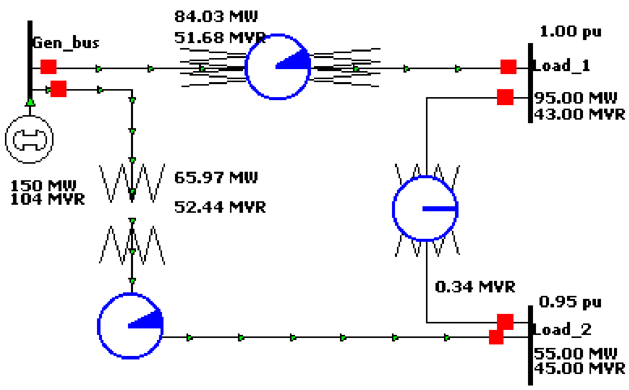

Figure 5 – A small power system

It can be seen in Table 2 that the following scenarios were analysed:

1. LTC transformer between buses 3 and 2 controls the voltage at the bus number 3 within the interval 0.96 – 0.98.
2. LTC transformer between buses 3 and 2 controls the voltage at the bus number 2 within the interval 0.98 – 0.985.

In the first scenario, the sensitivity $\frac{\Delta f}{\Delta t_{32}} = \frac{\Delta V_3}{\Delta t_{32}} = -0.32023$ is calculated in the second iteration of the N-R iteration procedure, because the controlled voltage $V_3 = 0.950782$ was out of the specified range, and correction of $\Delta V_3^{wanted} = 0.00921767$ was wanted. This correction requires the tap change of

$\Delta t_{32} = -0.028744$. After the tap position had been changed, a new iteration of the N-R procedure was carried out and the voltage at bus number 3 was changed to $V_3 = 0.960233159$. It should be noted that the voltage change is slightly larger than the wanted one, which is the consequence of the implemented linearisation. In the next iteration, the voltage at bus number 3 was $V_3 = 0.9599439$, which is still out of the specified range, but within an acceptable tolerance (0.002).

In the second scenario, the sensitivity $\frac{\Delta f}{\Delta t_{32}} = \frac{\Delta V_2}{\Delta t_{32}} = 0.318302$ was calculated in the second iteration of the N-R iteration procedure, because the controlled voltage $V_2 = 0.950174$ was out of the specified range, and correction of $\Delta V_2^{wanted} = 0.0298259$ was wanted. However, the sensitivity is now positive and consequently a positive tap change of $\Delta t_{32} = 0.0937$ is required. After the tap position had been changed, a new iteration of the N-R procedure was carried out and the voltage at bus number 2 was changed to $V_2 = 0.98180$. In the next iteration, the voltage at bus number 2 was $V_2 = 0.9785541$, which is still out of the specified range, but within an acceptable tolerance (0.002).

Tap Adjustments of Reactive Power Control Transformer on A Small Example

The same small power system example will be used to illustrate reactive power control transformer tap adjustments. Instead of the voltage control transformer between buses 3 and 2, a reactive power control transformer is connected. Therefore, the last row in Table 2 is changed as follows:

Table 2 Modified row – Transformer data

ID 1	ID 2	Automatic control	Control value	Lower Limit (control value)	Upper Limit (control value)	Lower tap limit	Upper tap limit
3	2	Yes	Reactive power control at the bus number 3	0.2	0.3	0.9	1.3

It can be seen in the modified Table 2 that the following scenario was analysed:

- Reactive power control transformer between buses 3 and 2 controls the reactive power flow at bus 3 within the range 0.2 – 0.3.

For this scenario, the sensitivity $\frac{\Delta f}{\Delta t_{32}} = \frac{\Delta Q_{32}}{\Delta t_{32}} = 2.580067$ was calculated in the second iteration of the N-R iteration procedure, because the controlled reactive power flow $Q_{32} = -0.00637$ was out of the specified range, and correction of $\Delta Q_{32}^{wanted} = 0.20637$ was wanted. The required tap movement was $\Delta t_{32} = 0.07998$ and the wanted changes of independent variables are:

$$\frac{\Delta \boldsymbol{x}}{\Delta t_{32}} = \begin{bmatrix} \Delta\theta_2 \\ \Delta\theta_3 \\ \Delta V_2 \\ \Delta V_3 \end{bmatrix} = \begin{bmatrix} 0.026756 \\ -0.021884 \\ 0.3366308 \\ -0.336474 \end{bmatrix} \Rightarrow \Delta \boldsymbol{x}^{wanted} = \begin{bmatrix} 0.0021399 \\ -0.00175 \\ 0.026923 \\ -0.026911 \end{bmatrix}$$

The change of independent variables calculated in the nest iteration of the N-R iteration procedure, after the tap change Δt_{32} took place was:

$$\Delta \boldsymbol{x} = \begin{bmatrix} 0.00229 \\ -0.00144 \\ 0.02821 \\ -0.02544 \end{bmatrix}$$

and the reactive power flow at the from bus was improved to $Q_{32} = 0.225$. No other change in the tap position was required during the iteration procedure.

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