A Quick and Comprehensive Method for Determining Static ATC with NRS and VFT

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ABSTRACT: Electricity market players prioritize available transfer capability (ATC) as an attractive solution. Market participants can gain a financial advantage through accurate and fast ATC solutions. In order to provide a suitable and valuable solution, we use differential load flow equations. A dynamic system’s entire time-domain trajectory can be solved by this method, along with a fictional time-domain differential equation. This article uses Newton-Raphson-Seydel instead of Newton-Raphson, which can also be used to determine voltage stability. A variable frequency transformer (VFT) was used in this study to increase and control transmission power. A 50% time saving on small systems was achieved with the proposed method, which was applied to seven different systems. In addition, it performed better on large systems by more than 90%. This proposal for static ATC presents promising results and can be applied to online applications.

Keywords: Available Transfer capability, Variable Frequency Transformer, Voltage Stability, Differential equation.

الملخص: يُعطي المشاركين في سوق الكهرباء أولوية للقدرة (ATC) بطريقة جذابة. يمكن للمشاركين في السوق الحصول على عائدات مالية من خلال حل ATC خلال دقيقة وسريعة. لتحديد حل مناسب وvido، نستخدم معادلات تدفق الحمل التقاطعية. يمكن حل مسار الزمن الكامل لنظام ديناميكي باستخدام هذه الطريقة، إلى جانب معادلة تكافؤية في المجال الزمني الوجودي. نستخدم هذا المقال قاعدة طريقة نيوتن-رافسون-سيدلي بدلاً من نيوتن-رافسون، والتي يمكن أيضاً استخدامها لتغيير استقرار الجهد. تم استخدام محاولة القدرة المتغيرة (VFT) في هذه الدراسة لإزالة وتحكم في قوة النظام. تم تحقيق نتائج بنسبة 50% على الأنظمة الصغيرة باستخدام نظام المستقر المثير، والذي تم تطبيقه على سعة أنظمة مختلفة. بالإضافة إلى ذلك، أدى بشكل أفضل على الأنظمة الكبيرة بأكثر من 90%. هذا الإفراز من ATC كلثيم نتائج واعدة ويُمكن تطبيقه على التقنيات المباشرة.

الكلمات المفتاحية: القدرة التحويلية المتاحة؛ محوّل التردد المتغير؛ استقرار الجهد؛ المعادلة التقاطعية.

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NOMENCLATURE

A: DEPF Jacobian matrix
B: End variables in the DEPF LF
B: DEPF load change in each direction
F_{new}: New LF equations
G_{DEPF}: DEPF general form of LF
J_{new}: New Jacobian matrix
P_L: Output power
P_e: Mechanical power of the drive system
P_F: Input power to the rotor
R_e, R_s: VFT impedance
X_{st}, X_{se}: VFT admittance matrix
V_p, V_L: Voltage and current of both sides of VFT
X_{old}: Old network variables
X_{new}: New general variables
Y_{VFT}: VFT variables
Y_{VFT}: VFT admittance matrix
Z_{VFT}: VFT impedance matrix
Y_0: NRS initial node injection
w: DEPF decompose the voltage
\lambda, \psi: Eigenvalues and eigenvectors
\theta_s: The angle of the rotor relative to the stator
\theta_{VFT}: VFT voltage angle
P_A: NRS search direction
A: NRS scaled search parameter
\Psi: DEPF loading parameter
X: NRS general variables
}\Xi: NRS load flow
\Theta: NRS Hessian matrix

INTRODUCTION

Energy sources are maximized by interconnecting power grids with asynchronous and synchronous methods (Khan et al. 2021). Asynchronous and synchronous connections are made with HVAC and HVDC transmission lines, respectively. As the backbone of the future transmission network, HVDC lines are considered in ATC calculations. HVDC transmission lines allow large amounts of power to be transferred, but the design and analysis of HVDC systems are quite complex and expensive (Khan et al. 2021).

Power can be exchanged between two asynchronous or synchronous networks using a variable frequency transformer (VFT) (Khan et al. 2021). The first VFT was installed and tested by GE in Langlois in 2004. With the VFT, power between electrical networks can be controlled more easily than before (Merkhouf et al. 2006). Assumed in this paper is that one VFT in the network determines optimal power transmission. It has long been an important issue in power system operation to calculate and send ATC every hour - both static ATC (SATC) (Liu et al. 2020, Eidiani et al. 2010) and dynamic ATC (DATC) (Eidiani 2021). DATC calculations are highly dependent on transient and voltage stability analysis (TSA-VSA) (Mohammed et al. 2019).

A general minimum residual method (GMRES) (Eidiani et al. 2010) can still be used to improve continuation power flow (CPF) (Zambroni et al. 2000) computations in SATC. The advantage of Newton-Raphson-Seydel (NRS) over NR is its faster and more accurate calculation of VSA and SATC (Eidiani et al. 2010).

ATC solution methods have been improved by incorporating artificial intelligence (AI) techniques into the optimal power flow calculation (OPF) (Lai et al. 1997). The ATC calculation was carried out using several AI methods, including cuckoo search, artificial neural networks, genetic and bee algorithms and particle swarm optimization (Lai et al. 1997). Total transfer capability’s (TTC) first contingency was limited by the high calculation time needed to compute unstable equilibrium points. ATC can be approximated with acceptable speed and accuracy using the Jacobian matrix determinant, transient stability and peak of potential energy method (Kim et al. 2000).

The DATC calculation with renewable sources on networks was presented using the support vector regression (SVR) method from 2012 to 2020 (Shaban 2018). A probabilistic power flow (PPF) approach for accessing SATC was proposed in (Karuppasamy pandyian et al. 2020). According to the results, this method provides a more accurate and effective evaluation of SATC.

An optimal power flow problem under transient stability constraints (TSC-OPF) can be used to estimate total transfer capability (Zhang et al. 2020). The state estimation program should also be used to calculate load flow (LF) parameters (Eidiani 2021).

There is no simplification or initial guessing required with the holomorphic embedding power flow (HEPF) algorithm (Eidiani 2021), although it has a long computation time. Using the differential LF approach, transient stability simulations can be solved effectively (Eidiani 2021). A numerical algorithm that does not require iteration is developed by the researchers in (Eidiani 2021) in order to solve nonlinear AC load flows. An embedding of differential equation power flow (DEPF) into the proposed method (SATC-DE) was used in the current work. Additionally, this study used DEPF (Eidiani 2021)'s initial model and improved the method of calculating Static ATC (SATC). With the developed model, large and practical systems can be analyzed with less computational overhead and consistent performance.

We describe here the key characteristics of the new SATC evaluation method with VFT. We developed a differential equation-based SATC calculation in the presence of VFT in this study. The new algorithm is based on the initial work on the differential equation LF algorithm that was published in (Eidiani 2021), which showed efficiency in terms of dynamic LF. In section 2, DEPF with NKS and VFT model is defined, and in section 3, the proposed approach for SATC assessment with VFT is discussed. The fourth section presents the results and discussions.
Lastly, the proposed method is tested on several bi- and multilateral contract systems.

**DEPF WITH NRS AND VFT MODEL**

An illustrated network connection for VFT can be seen in Figure 1, and a simplified circuit diagram for VFT can be seen in Figure 2.

![Figure 1](image1.png)

**Figure 1.** An illustrated network connection for VFT (Khan et al. 2021)

![Figure 2](image2.png)

**Figure 2.** A simplified circuit diagram for VFT (Merkhouf et al. 2006)

The relationship between $P_g$, $P_d$, and $P_L$ is shown in Figure 1. $P_L$ is the output power, $P_d$ is the mechanical power of the drive system, and $P_g$ represents the input power to the rotor.

$$P_g + P_d = P_L$$  \hspace{1cm} (1)

The following are bipolar equations that can be used to calculate VFT's voltage and current equations (Figure 2).

$$\begin{bmatrix} V_g \\ V_L \end{bmatrix} = \begin{bmatrix} Z_{VFT} & J_g \\ J_L & Z_{VFT} \end{bmatrix} \begin{bmatrix} I_g \\ I_L \end{bmatrix} \Rightarrow$$

$$\begin{bmatrix} I_g \\ I_L \end{bmatrix} = \begin{bmatrix} Y_{VFT} & V_g \\ V_L & Y_{VFT} \end{bmatrix} \begin{bmatrix} V_g \\ V_L \end{bmatrix}$$  \hspace{1cm} (2)

Equation (2) can be applied to the LF equation, and the VFT angle (δ) can be varied to adjust the transfer power between the rotor and stator. Increased ATC can be achieved by controlling power at the VFT, which then controls power at the transmission line.

It should be noted that in a VFT, where torque is applied to the rotor, the induced Emf in the coil of the rotor remains constant, but its phase angle changes by $\theta_{rs}$. The following real equations are obtained by simplifying the LF equations in Figure 2.

$$V_L \sin \theta_{rs} = I_g X_m \cos (\phi_g + \theta_{rs}) - I_L X_s \cos \phi_L$$

$$-I_L X_m \cos \phi_L - I_L R_{s} \sin \phi_L$$

$$V_L \cos \theta_{rs} = I_g X_m \sin (\phi_g + \theta_{rs}) + I_L X_s \sin \phi_L$$

$$-I_L X_m \sin \phi_L - I_L R_{s} \cos \phi_L$$

$$V_g \sin (\theta_{rs} + \theta_g) = (X_m + X_s) I_g \cos (\theta_{rs} + \phi_g)$$

$$-I_L X_m s \cos \phi_L + I_L R_{s} \sin (\theta_{rs} + \phi_g)$$

$$V_g \cos (\theta_{rs} + \phi_g) = -(X_m + X_s) I_g \sin (\theta_{rs} + \phi_g)$$

$$+ I_L X_m s \sin \phi_L + I_L R_{s} \cos (\theta_{rs} + \phi_g)$$

The main LF equations can be easily modified by deriving LF flow equations (3). We can replace old network variables ($X_{old} = [\delta J^T]$) with new general variables ($X = X_{new} = [X_{old}, X_{VFT}]$) by defining VFT variables as ($X_{VFT} = [\theta_{rs}, \phi_{rs}, \theta_{gs}, \phi_{gs}, V_g, V_L]^T$). It is now possible to calculate the new LF equations and the new Jacobian matrix of the network.

$$F_{new}(X_{new}) = 0 \Rightarrow \Delta F_{new} = J_{new} \Delta X_{new}$$  \hspace{1cm} (4)

Or:

$$\Delta F_{new} = J_{new} \Delta X_{new} \Rightarrow \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_{p0} & J_{pV} & J_{pX_{VFT}} \\ J_{q0} & J_{qV} & J_{qX_{VFT}} \end{bmatrix} \begin{bmatrix} \Delta \theta \\ \Delta V \end{bmatrix}$$

$$\Rightarrow \frac{\partial \Xi}{\partial \chi} = \Xi(\chi) = \begin{bmatrix} J_{new} v - \lambda v \\ v_0 + \rho a + F_{new}(X) \end{bmatrix} = 0 \Rightarrow$$

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$$\frac{\partial \Xi}{\partial \chi} = \begin{bmatrix} \Theta J_{new} - \lambda I & 0 \\ 0 & \frac{v^2}{|v|^2} \end{bmatrix}$$

$$\frac{\partial F_{new}}{\partial X} = \begin{bmatrix} 0 & -\rho \end{bmatrix}$$

That:

$$\Theta = \frac{\partial F_{new}}{\partial X} \begin{bmatrix} v_1 \\ \vdots \\ v_n \end{bmatrix} = \begin{bmatrix} \frac{\partial}{\partial X_{1_{new}}} J_{new} v \\ \vdots \\ \frac{\partial}{\partial X_{n_{new}}} J_{new} v \end{bmatrix}$$  \hspace{1cm} (7)
And:
\[
\text{inv} (\Xi (\chi)) = \left[ \begin{array}{c}
\Theta \\
\Xi_{z1} \\
\Xi_{z2}
\end{array} \right]^{-1} = \\
\left[ \begin{array}{c}
\Theta^{-1} (I - \Xi_{z1} \Xi_{z2} (\Theta^{-1})^T) - \Theta^{-1} \Xi_{z2} \Xi_{z1} \\
-\Xi_{z1} \Theta^{-1} \\
\Xi_{z1} \Xi_{z2}
\end{array} \right]^{-1} \\
\Xi = (\Xi_{z2} - \Xi_{z1} \Theta^{-1} \Xi_{z1})^{-1}
\]
(8)

The NRS equation can now be combined with the DEPF equation. The proposed method solves a linear equation only once per time step, whereas the CPF method solves it in every correction-prediction step. We now briefly review the DEPF approach (Eidiani 2021). DEPF calculations are based on the concept of converting continuous-time parameters into discrete variables like $w(t) \rightarrow W(k)$. The normal LF is depicted in (9), where $(b)$ is the load change in each direction and $\psi$ is the loading parameter.

\[
I = YV \Rightarrow S = V't = V'(V^{-1}V')' \Rightarrow \\
S + \psi b = VY'V^*'
\]
(9)

In order to decompose the voltage, we need to do the following:

\[
w = [\text{real} (V'), \text{imaginary} (V')]
\]
(10)

It is now possible to write (10) as (11) in the general form.

\[
g_{\text{depf}} (\psi, w) = 0
\]
(11)

DEPF defines a reversible relationship for changing variables as (12).

\[
w (t) = \sum_{k=0}^{K} \left[ \text{w} (k) \right] \Leftrightarrow W (k) = \frac{1}{k} \left[ \frac{d}{dt} \text{w} (t) \right] |_{t=0}
\]
(12)

First, the DEPF method expands the algebraic equation (11) by adding a state variable ($x$) to a set of DAEs. We obtain the following linear equation by linearizing all the equations using (12). As a result, we can obtain the Jacobian matrix of the method as follows (Eidiani 2021):

\[
\begin{bmatrix}
W (k) \\
\Psi (k)
\end{bmatrix} = \begin{bmatrix}
A_{12} & A_{11} \\
A_{21} & A_{22}
\end{bmatrix}^{-1} \begin{bmatrix}
B_1 \\
B_2
\end{bmatrix}
\]
(13)

The nonlinear LF equation (14) is solved using ($A_{i1}A_{i2}$) matrices in a differential transformation (Eidiani 2021). We have:

\[
\begin{bmatrix}
W (k) \\
\Psi (k)
\end{bmatrix} = \begin{bmatrix}
A_{11} (I + A_{12} A_{22} A_{21}) - A_{11} A_{12} A_{21} \\
-A_{12} A_{21}
\end{bmatrix}^{-1} \begin{bmatrix}
B_1 \\
B_2
\end{bmatrix}
\]
(14)

DEPF model’s key characteristics helped us find a simple and user-friendly SATC solution in an accurate and fast manner.

THE PROPOSED METHOD OF SATC

LFs are calculated using the DEPF approach at the contract update with a decrease or increase in loading parameters. SATCs have been determined for normal and contingency cases. An algorithm for assessing SATC using DEPF, NRS, and VFT can be seen in the following.

1- All network information, controllers, and sales contracts should be entered.
2- For each bi/multilateral contract (i) between seller and buyer, change the vector of load direction in (9) accordingly.
3- Utilize the DEPF method developed in the previous section of this contract to find the maximum load parameter.
4- In this contract, calculate the ATC for normal and contingencies.
5- Using the previous steps, determine the maximum allowable transmission power between buyer and seller.
6- At each contract, evaluate SATC.
7- If the type of contract is changed, the algorithm goes back to step 1 until the final contract.

It is similar to the previous section in the SATC calculation after the generator is lost or disconnected, except the bus type changes to PQ. A parallel line with negative impedance can also simulate a line disconnected. Lines and transformers have a maximum thermal load limit of 100%, active power of 0 to 90%, a reactive power of 50% to -50%, and a maximum voltage difference of 5%. This method shows high speed and accuracy in several networks based on the above conditions.

RESULTS AND DISCUSSIONS

DiSILENT PowerFactory and MATLAB were used to simulate the proposed SATC model. We studied developed mode performance on a computer with Core i7 (Intel), 2 cores, 2.3GHz, 8GB RAM. We tested the proposed SATC on a number of systems, including 40 (Link 1), 120 (Link 1), 150 (Eidiani 2021), 300 (Link 1), 4440 and 1150 (Liu et al. 2020) and 6070 (Link 2). Several approaches are compared with the simulation results of the new method, including HEFP (Eidiani 2021), NRS (Eidiani et al. 2010), SATC (Eidiani 2021), CPF-GMRES (Eidiani et al. 2010) and CPF (Zambroni et al. 2000).
SATC solutions calculated using six methods, seven systems and four multilateral and 21 bilateral transactions are shown in Table 1. A comparison was made between the proposed method’s Root Mean Square Error (RMSE) and Calculate Relative Speed (CRS) (Table 2). There is no direct correlation between the number of buses and the CRS. In terms of execution time, the proposed method outperforms other approaches. It was found that the new method consumed nearly half the processing time compared to the other methods on average. As shown in Table 2, even if there is VFT, the proposed method is faster than the usual methods.

Figure 6 illustrates the root mean square errors between the proposed method and the other approaches, both with and without the VFT. The accuracy of the SATC solution found by all approaches varies from 0.08% to 2%, compared with the accuracy of ATC calculated based on CPF. In comparison to conventional methods, the proposed method takes almost 40% to 60% less time to calculate SATC, and 8% less time than HEPF. In comparison with the contender methods, 65 to 90% of the time can be saved, as well as 15% more than with HEPF.

The outcome of the study indicates that the proposed approach facilitates the computation of SATC calculations that are nearly 25% to 90% computationally efficient, proving that the developed model is both practical and suitable for online use. Based on the simulation results, the most precise method is the conventional CPF method used as a benchmark. CPF, on the other hand, is the closest approach to the new method. In addition, the developed approach was shown to be readily applicable for distribution systems as well, thus extending its robustness beyond transmission networks.

Table 2. Comparing the CRS of the proposed method with other methods with and without VFT, Methods (M.) and systems (S.) are similar to Table 1

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Figure 3- Comparing the proposed method with other methods with and without VFT
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Table 1. SATC (p.u.) and Error (Er), with (W/.) and without (W/o) VFT Methods (M): 1-CPF (Zamboni et al. 2000), 2-CPP-GMRES (Eidiani et al. 2010), 3- NRS (3) (Eidiani et al. 2010), 4- SATC (4) (Eidiani 2021), 5- HEPF (5) (Eidiani 2021) and 6- The proposed method. Systems (S): 1-40 (Link 1), 2-120 (Link 1), 3-150 (Eidiani 2021), 4-300 (Link 1), 5-1150 and 6-4440 (Eidiani 2021) and 7-6070 (Link 2).
CONCLUSION

A new algorithm based on differential power flow equations and Newton-Raphson-Seydel was developed to calculate static available transmission capacity. In this paper, a power controller called a Variable Frequency Transformer is used to increase power. This controller complicates calculations. Several test systems were examined, including standard IEEE systems as well as large-scale and practical utility systems, to demonstrate the method’s ability. The new method increases calculation speed and reduces calculation error compared to existing methods with VFT. Accordingly, the proposed SATC method provides accurate results while taking less CPU time to complete than other methods. As a result, the proposed method has the potential to be applied online in large transmission and distribution networks with VFT.

CONFLICT OF INTEREST

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REFERENCES