# CAPABILITY ASSESSMENT OF DISTRIBUTION NETWORK REACTIVE POWER SUPPORTS FOR TRANSMISSION NETWORK USING LINEAR ESTIMATION

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## ABSTRACT

*Transmission System Operators (TSOs) are currently experiencing a voltage rise problem on their network, especially during the periods of low demands. It is costly to mitigate the excessive voltages by installing reactors or Var compensators in transmission network. Recently, an alternative method of utilising the existing parallel transformers of distribution network is proposed. It uses a tap stagger technique, to address this problem. This paper investigates the VAr support capability of the tap stagger technique with the method of linear estimation. Two real different-sized sub-distribution networks are modelled and their load flow results with the tap stagger operation are studied. Then the capability for the whole distribution network is estimated by the linear estimation method. The results indicate the capability is high and show the potential to provide sufficient reactive power services to transmission systems.*

## INTRODUCTION

With the progress of low carbon network in power sector, it is expected to connect more and more distribution generations (DG) with renewable resources into distribution networks. Because of the intermittent output of DGs, network voltages may exceed the statutory limit at some times. In addition, the voltage rise problem could also happen in transmission network. In the transmission system of England and Wales, a number of voltage excursions have been reported every year [1]. Based on the report [2], at times of low demand, especially low reactive power demand, voltages on transmission network can increase naturally due to capacitive gain. Apart from the abnormal decline of the overnight reactive power demand, another main reason which causes voltage rise is the development of underground cables in both transmission and distribution networks due to their large capacitance. High voltages need to be controlled to avoid damaging the equipment, so enough reactive compensation and switching options are critical to effective voltage control.

Traditionally, in power system, the means of reactive power management include through the control of generators, shunt capacitor banks, shunt reactors, and static VAr compensators. However installing reactors or VAr compensators in transmission system is usually expensive and time-consuming. In [3-5], many efforts have been made on developing reactive power dispatching optimization algorithms. The traditional multi-object Var optimization is aimed to obtain the minimum for active power loss and total voltage deviation while satisfying the constraints. In [6-8], the VAr balancing provided by wind farm connected to transmission networks has been investigated. A multilevel control system has been proposed in [6] to regularly calculate the references of all wind turbines. In [7], Particle Swarm Optimization method has been proposed to define reference voltages of decentralized wind farms with full reactive power capability. In [9], as reactive power ancillary service providers, the technical and cost models of wind farms have been developed.

Due to the intermittent renewable resources, the overvoltage issues in transmission network may happen at various places and time periods. In traditional way, to address it, a great number of VAr compensators need to be installed. Alternatively a comparatively cost-effective method of VAr support for transmission network has been studied recently [10]. It utilizes the existing parallel transformers operated at staggered taps at primary substations of distribution network to absorb VAr surplus in transmission system. This is known as 'tap stagger' technique, which means one transformer is set to an off-nominal ratio of, say, 1.1 : 1 and the other to 0.9 : 1 (i.e. in opposite directions), then a circulation of reactive power occurs round the loop, resulting in a net absorption of VAr. In [11], the annual cost of applying tap stagger technique has been compared with using passive compensators. The transient response of transmission voltage to tap stagger has been investigated. In [12], the reactive power absorption capability of distribution network by applying tap stagger has been assessed based on randomly selecting parallel transformers method.

This paper proposes to use a linear estimation method to calculate the overall reactive power support capability of a real UK distribution network from Electricity North West (ENW), one of UK distribution network operators. In the studies, two sub-distribution networks, connected with Grid Supply Point (GSP) to the UK National Grid respectively, are selected. One is a light-loaded, small-scaled with a number of distributed generators and the other is a heavy-loaded with a larger distribution network size. These two sub-networks are modelled and simulated using OpenDSS, a power system simulation tool. The load flow simulations are carried out on the two modelled subnetworks with different tap staggering operation to obtain each sub-network reactive power absorption capability. Based on the result of each substation's capacity, a linear estimation method is applied to obtain the reactive power absorption capability for the whole typical distribution network.

## SUB-DISTRIBUTION NETWORK MODELS

Fig. 1 illustrates the basic structure of whole ENW HV distribution networks with various voltage levels.

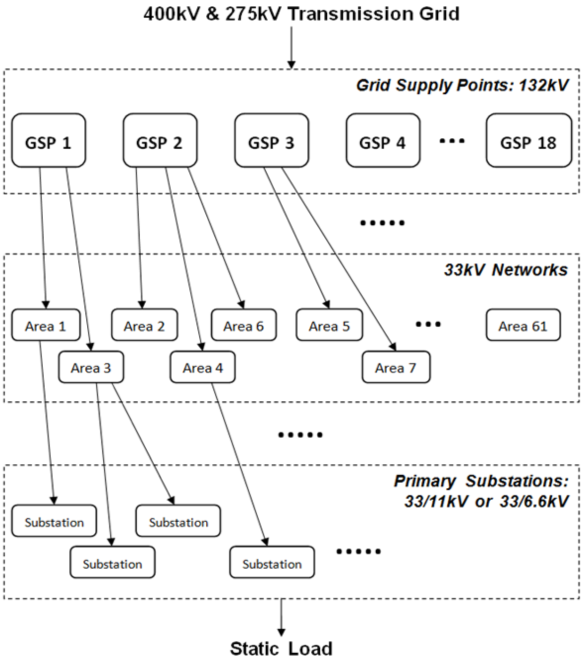

Fig. 1 The structure of whole ENW HV distribution networks

As shown in Fig. 1, distribution network is constructed as radical network with main power sources from transmission grid at 400 kV and 275kV. Electricity is transformed from transmission grid to distribution 132kV networks through grid supply points (GSP). Totally, in ENW, it has 18 GSPs connected on its distribution networks. Then electricity is distributed throughout 33kV networks to load areas. In each load area, there is at least one primary substation (PS), (i.e. 33/11kV or 33/6.6kV), where the tap stagger technique is implemented. The downstream 11kV or 6.6kV networks are model as constant loads connected at secondary sides of PSs.

Each of the sub-distribution networks modelled in this paper includes one GSP, and its whole downstream network down to 11 or 6.6kV. Table 1 shows the parameters of the two modelled sub-distribution networks.

Table 1: Parameters of two modelled sub-distribution networks

| | South Manchester Subnetwork | Stalybridge Subnetwork |
|---|---|---|
| GSP Name | South Manchester GSP | Stalybridge GSP |
| Total power rating | 178MW 88MVAr | 434MW 236MVAr |
| Average power factor | 89.56% | 87.88% |
| No. of PSs | 11 | 28 |
| No. of DGs | 5 | 0 |
| No. of transformers | 33 | 76 |
| No. of buses | 102 | 222 |

According to the table, South Manchester subnetwork is light-loaded, small-scaled with five distributed generators, while Stalybridge Subnetwork is heavy-loaded with a larger distribution network size. Both of them are modelled and simulated in OpenDSS.

## METHODOLOGY OF LINEAR ESTIMATION

The flow chart of the studied method is given in Fig. 2. The detail explanation is described below.

1) Perform the initial load flow simulation in the OpenDSS network model without tap stagger. Then set all primary substation transformers with Stagger = 1 (i.e. 1 tap up for one transformer and 1 tap down for the other) and perform the load flow study. Repeat the simulation with Stagger = 2, 3, and 4, respectively. The maximum 4 tap stagger is proposed considering the general physical tap headroom limitation in transformers. Record the Q and P values at the GSP 132kV side for all simulations. At this stage, all loads are fixed at their default rated values.

2) Subtract the initial Q and P values (obtained without tap stagger) from the Q and P values obtained with stagger, to calculate the extra Q absorption and P loss caused by the tap stagger.

3) Take the average of the results in step (2) to represent the average Q absorption and P loss per primary substation (due to tap stagger).

4) As the network is a radial distribution network, it is assumed that the total Q absorption and P loss of the network will increase linearly with the number of primary substation transformers using tap stagger. Therefore, the Q absorption and P loss for the Electricity North West network can be estimated by multiplying the results in step (3) with the total number of primary substations in the Electricity North West network.

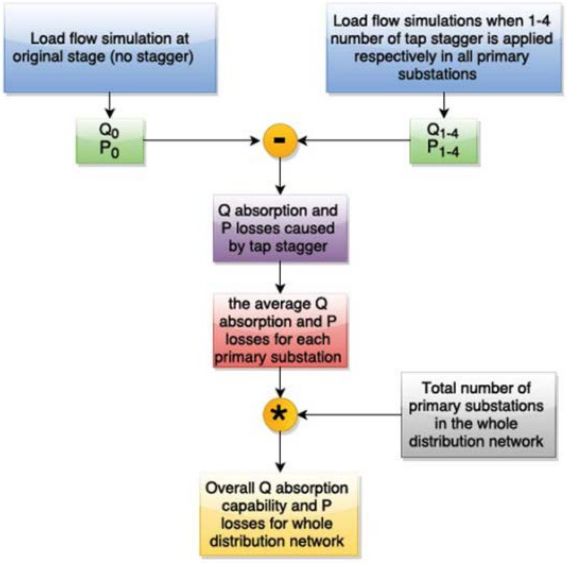

Fig. 2: Methodology of reactive power support capability assessment

The estimated Q absorption capability and P losses for the whole distribution network due to tap stagger operation can be expressed as:

$$Q_{absorb}^{i} = \frac{Q_{stagger}^{i} - Q_{original}}{N_0} \times N_d \qquad (1)$$

$$P_{loss}^{i} = \frac{P_{stagger}^{i} - P_{original}}{N_0} \times N_d \qquad (2)$$

Where, ‘i’ represents the number of staggered taps that has been set (i.e. ‘i’ taps up for one transformer and ‘i’ taps down for the other). $N_0$ and $N_d$ denote the number of pairs of parallel transformers for modelled sub-distribution network and the whole distribution network respectively.

## RESULTS AND ANALYSIS

The linear estimation method described above has been applied to the South Manchester and the Stalybridge sub-distribution network models. The results are indicated in Table 2 and Table 3, respectively.

Table 2: Additional *Q* absorption and *P* loss of the South Manchester

| South Manchester sub-distribution model | | | | | |
|---|---|---|---|---|---|
| No. of stagger | 0 | 1 | 2 | 3 | 4 |
| P at GSP(MW) | 164.66 | 164.70 | 164.80 | 164.97 | 165.21 |
| Q at GSP(MVAr) | 10.162 | 10.766 | 12.585 | 15.613 | 19.843 |
| Extra P loss(MW) | 0 | 0.036 | 0.140 | 0.310 | 0.546 |
| Extra Q absorption (MVAr) | 0 | 0.604 | 2.423 | 5.451 | 9.681 |
| P loss per PS(MW/PS) | 0 | 0.003 | 0.013 | 0.028 | 0.050 |
| Q absorption per PS(MVAr/PS) | 0 | 0.055 | 0.220 | 0.500 | 0.880 |

Table 3: Additional *Q* absorption and *P* loss of the Stalybridge model

| Stalybridge sub-distribution model | | | | | |
|---|---|---|---|---|---|
| No. of stagger | 0 | 1 | 2 | 3 | 4 |
| P at GSP(MW) | 433.64 | 433.75 | 434.04 | 434.53 | 435.14 |
| Q at GSP(MVAr) | 208.66 | 210.41 | 215.36 | 223.48 | 233.84 |
| Extra P loss(MW) | 0 | 0.106 | 0.401 | 0.885 | 1.503 |
| Extra Q absorption (MVAr) | 0 | 1.744 | 6.692 | 14.819 | 25.178 |
| P loss per PS(MW/PS) | 0 | 0.004 | 0.014 | 0.032 | 0.054 |
| Q absorption per PS(MVAr/PS) | 0 | 0.062 | 0.239 | 0.530 | 0.900 |

As shown in Table 2, the additional Q absorption for all 11 pairs of parallel transformers with Stagger = 1 is 0.604 MVAr. The reactive power absorption increases to 9.681 MVAr for all parallel transformers with Stagger = 4 (i.e. 4 taps up for one transformer and 4 taps down for the other). In terms of the Stalybridge network model, Table 3 indicates that the *Q* absorption of the total 28 pairs of parallel transformers with Stagger = 1 is 1.744 MVAr. The reactive power absorption increases to 25.178VAr for all parallel transformers with Stagger = 4. From Table 2 and Table 3, the P losses introduced by the tap stagger are generally 17 times smaller than the created *Q* absorption.

Assuming all primary substation transformers (i.e. a total of 354 pairs) in the Electricity North West network can contribute to the reactive power absorption service, the total VAr absorption capability has been estimated using the linear approximation (as presented in Fig. 2). Table 4 shows the result, based on the South Manchester network study.

Table 4: Estimated *Q* support capability of whole ENW network based on the South Manchester network study

| Capability for whole ENW network based on results of South Manchester sub-distribution network | | | | |
|---|---|---|---|---|
| No. of stagger | 1 | 2 | 3 | 4 |
| Total P loss (MW) | 1.2 | 4.5 | 10.0 | 17.6 |
| Q support Capability (MVAr) | 19.4 | 78.0 | 175.4 | 311.5 |

In addition, Table 5 indicates the estimated reactive power absorption capability of the Electricity North West network based on the Stalybridge network study.

Table 5: Estimated *Q* support capability of whole ENW network based on the Stalybridge network study

| Capability for whole ENW network based on results of Stalybridge sub-distribution network | | | | |
|---|---|---|---|---|
| No. of stagger | 1 | 2 | 3 | 4 |
| Total P loss (MW) | 1.3 | 5.1 | 11.2 | 19.0 |
| Q support Capability (MVAr) | 22.1 | 84.6 | 187.4 | 318.3 |

From Table 4 and Table 5, it shows the results obtained from the two network models are close to each other although the two networks have different sizes and loading conditions. By taking the average of the two network study results, Table 6 shows the average VAr absorption capability of the Electricity North West network.

Table 6: Average *Q* absorption capability of the Electricity North West network

| Averaged capacity for whole ENW network based on two models | | | | |
|---|---|---|---|---|
| No. of stagger | 1 | 2 | 3 | 4 |
| Total P loss (MW) | 1.25 | 4.78 | 10.57 | 18.29 |
| Q support Capability (MVAr) | 20.74 | 81.29 | 181.39 | 314.93 |

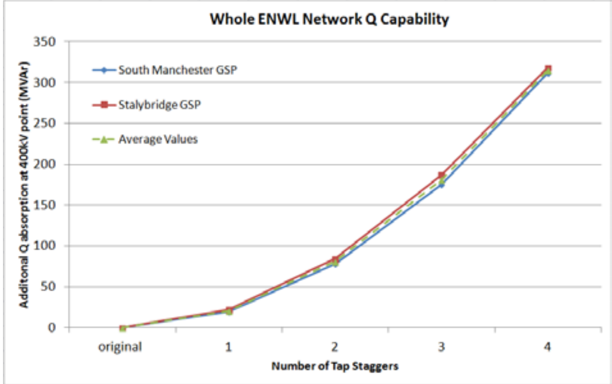

Fig. 3: Estimated VAr absorption capability for the whole ENW distribution network based on the two modelled networks

Fig. 3 plots the estimated VAr absorption capability of the Electricity North West network based on the two modelled networks studies and their averaged values. According to the results, the average *Q* absorption capability per primary substation is 0.06 MVAr at Stagger = 1, 0.23 MVAr at Stagger = 2, 0.51 MVAr at Stagger = 3 and 0.89 MVAr at Stagger = 4. The corresponding power losses introduced by tap stagger are 0.004 MW, 0.01 MW, 0.03 MW and 0.05 MW per primary substation, respectively.

Note that the simulations have tested the transformers with staggered taps up to 4. However, in practice, the initial tap position of each primary substation transformer will be determined by the load condition. In some cases, the transformer tap positions may only have limited headroom to operate with Stagger = 1 or 2. Therefore, the studies with fixed load demands may overestimate the VAr absorption capability of the Electricity North West EHV network. To refine the estimation results, the capability studies considering the network with various load demands will be investigated in the future.

## CONCLUSIONS

This paper introduces the reactive power support method which utilises parallel transformers in distribution networks operated in staggered tap positions. A linear estimation method has been proposed for assessing the overall reactive power support capability of tap stagger technique from distribution network to transmission network. For achieving the assessment, two sub-distribution networks of ENW are modelled in OpenDSS and then the load flow studies have been carried out with tap stagger operations. The overall VAr support capability of the whole ENW distribution network has been estimated using the proposed linear estimation method. The results reveal the potential of distribution network to provide sufficient reactive power services to transmission system in a cost-effective way. To further refine the results, in the future, load profiles should be involved to investigate VAr support capabilities at different load conditions.

## ACKNOWLEDGMENT

The author would like to appreciate Electricity North West (ENW) for providing distribution network data to facilitate networks modelling in this paper.

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