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Mitigating tap changer limit cycles in modern electricity networks embedded with local generation units

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Abstract

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Keywords

changer, tap, local, embedded, networks, electricity, modern, units, cycles, generation, limit, mitigating

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Mitigating Tap-changer Limit Cycles in Modern Electricity Networks Embedded with Local Generation Units

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***Abstract*--Cascaded on-load tap changers (OLTC) are widely used for coarse control of voltage in largely interconnected electric power systems. There could be interactions between load dynamics and OLTC control under certain system operating conditions which may lead to OLTC limit cycle phenomena thereby resulting into long term voltage oscillations in the system. In recent years, renewable and non-renewable local generation units have been getting interconnected in modern power systems. The existence of OLTC limit cycles in the presence of local generation has not been addressed in the literature in greater details. In this paper, the OLTC limit cycle phenomena, which can occur due to interactions among load dynamics, OLTC controls and the local generation operation in electricity networks has been investigated. Also, a novel strategy is explored for mitigating the power system oscillations introduced by OLTC limit cycles, especially for a network embedded with local generation. The proposed mitigation strategy including detailed investigations and analyses have been verified for a two-bus test system, and successfully tested on a multi-bus system using MATLAB.**

***Index Terms*--Limit-cycle phenomena; load dynamics; local generation; on-load tap changer; power system oscillations.**

I. INTRODUCTION

IN electric power systems, there are various potential sources of the system oscillatory behavior. One of the sources is on-load tap changer (OLTC) limit cycles resulted due to interactions between OLTC and load dynamics. It can be observed that the power systems with OLTC limit cycles are likely to experience sustained long term oscillations under certain operating conditions. On the other hand, the research on voltage behavior reveals that the dynamics of voltage collapse are closely related to the dynamic interactions among OLTCs and system loads. It is because OLTCs maintain load voltages within stipulated limits though transmission system voltages may be reduced. Therefore in case of long term voltage collapse, OLTC limit cycles play a key role. One of the novel contributions of this paper is that the OLTC limit cycles can occur frequently in case of electricity networks embedded with LG units due to interactions among load, OLTC control and the LG unit operation. The recurrence of OLTC limit cycles in the presence of LG under any practical system operation can be high, as predicted, compared to the system operation without LG. The OLTC limit cycles may sustain for a longer time especially under flat load profiles or load profiles with slow ramp variations. Also, it would adversely affect the system Volt/VAr control mechanisms and objectives. Moreover, it leads to (a) numerous tap operations (up and down) causing rapid wear and tear in tap changing devices, and (b) interactions among voltage control devices in the system.

In [1], the existence of OLTC limit cycles is investigated and analyzed. The system load level, degree of reactive power compensation and the load-voltage dependency are identified as the key parameters for initiation and avoidance of the OLTC limit cycles. The nature of limit cycles caused by the interaction between transformer tap changer and load dynamics is analyzed in [2]. A linearization of Poincar´e map is used to analyze the local stability in the system under OLTC limit cycles. In [3], voltage oscillations in power systems with cascaded multiple OLTC units have been studied, where the focus is on the limit cycles due to interactions among tap changers and system loads. Also, a control strategy is proposed in [3] to mitigate the OLTC limit cycles. It is based on adjusting the dead-band (DB) of the tap changer, which typically depends on the load characteristics. It has been found that the existing limit cycles can be avoided and a steady-state condition is reached given a sufficiently large DB in case of stable load dynamics when tap ratios are fixed. The existing limit cycles will not be removed by increasing DB in case of unstable load dynamics wherein tap ratios are fixed. Moreover, it has been found that adjusting OLTC control parameters such as time delay and/or DB size may not have any effect on the existence of limit cycles under certain system conditions [1]. It may not be possible to avoid limit cycle behavior simply by retuning the OLTC dead-band limit and/or time delay. However, none of the studies in the literature have investigated and analyzed the OLTC limit cycle phenomena in electricity networks with higher penetration of renewable and non-renewable local generation (LG). For such networks, OLTC limit cycles can occur frequently due to interactions among load, OLTC control and the local generation operation.

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In this paper, OLTC limit cycle phenomena in case of medium voltage (MV) electricity networks with higher penetration of LG is investigated and analyzed thoroughly. The small signal model and describing function method used in [1] for OLTC limit cycle analysis in a two bus system have been extended for analyzing and predicting OLTC limit cycles in multi bus system topology with LG. Also, a strategy based on coordinated VAr support from LG units and shunt capacitor banks (CBs) is explored in order to mitigate the OLTC limit cycles in the presence of LG units. It is easily implementable with a typical voltage control scheme. In this paper, MATLAB is used for modeling the sample power systems and conducting associated simulation studies.

This paper is organized as below. Section II outlines the theoretical background of the paper relating to investigating and analyzing the OLTC limit cycles and Section III elaborates the algorithm of the proposed strategy for mitigating OLTC limit cycles including realistic case study. The concluding remarks have been made in Section IV of the paper.

II. Background Theory

A. Predicting Existence of OLTC Limit Cycles

Eigen value analysis is used to predict the existence of OLTC limit cycles, and the results are compared with describing function analysis. For large MV power systems, network reduction methods can be applied to minimize the computational burden [4].

1) Modeling Aspects

The model described by the dead band-ordinary differential equation (DB-ODE) is used for modeling OLTC as given by (01) [5]. It is noted that discrete tap steps are not taken into account in this OLTC model. While analyzing OLTC limit cycles using the proposed small-signal analysis, it was noted that the overall behavior of the moderately loaded power systems is largely similar for continuous as well as discrete OLTC models. However, it could be otherwise under heavy loading conditions, which is insignificant in presence of LG units as the local load is supplied by the LG. Under heavy load conditions, the systems with discrete OLTC model exhibits a limit cycle that will arrest oscillatory voltage instability predicted by small-signal analysis, whereas the system with the continuous models shows voltage collapse after a few cycles. These aspects are detailed in [1]. However, the prediction of OLTC limit cycles in power systems using the proposed small-signal analysis is accurate for both cases. Also, it is to be noted that the limit cycles in the power system are associated with its mathematical model and not with the numerical problems in the simulation. In this paper, the small-signal analysis is used to predict the occurrence of OLTC limit cycles in power systems embedded with LG units and a new control strategy is proposed to mitigate long term sustained oscillations in the system.

The V_{LC} denotes regulated voltage at the regulating point, V_{set} is the voltage set value, T is the OLTC controller time delay and n is the transformer tap-ratio.

$$\frac{dn}{dt}=\begin{cases}(-)\,\frac{1}{T}.(V_{LC}-V_{set}-DB/2) & \text{if } (V_{LC}-V_{set})>DB/2\\ (-)\,\frac{1}{T}.(V_{LC}-V_{set}+DB/2) & \text{if } (V_{LC}-V_{set})<(-)DB/2\\ 0 & \text{if } |V_{LC}-V_{set}|<DB/2\end{cases} \tag{01}$$

Accurate modeling of different load characteristics is one of the key requirements of analyzing and predicting OLTC limit cycles. In this paper, the loads are modelled as exponential recovery loads as given by (02) and (03) [4].

$$\dot{x}_p=\frac{1}{T_p}\left(-x_p+P_s(V)-P_t(V)\right),\qquad P_s(V)=k_L.P_0(V)^{\alpha_s}$$
$$P_t(V)=k_L.P_0(V)^{\alpha_t},\qquad P_d=x_p+P_t(V) \tag{02}$$
$$\dot{x}_q=\frac{1}{T_q}\left(-x_q+Q_s(V)-Q_t(V)\right),\qquad Q_s(V)=k_L.Q_0(V)^{\beta_s}$$
$$Q_t(V)=k_L.Q_0(V)^{\beta_t},\qquad Q_d=x_q+Q_t(V) \tag{03}$$

where, x is an internal state which models the load recovery dynamics. The recovery time constants are T_p and T_q, and α_s, α_t, β_s, β_t are the exponents of the voltage. The steady state nodal voltage dependency of loads is denoted using $P_s(V)$ and $Q_s(V)$, where the transient (instantaneous) nodal voltage dependency is denoted using $P_t(V)$ and $Q_t(V)$ respectively. The P_d and Q_d denote actual loads where the rated load values are denoted using P_0 and Q_0. The load scale factor is k_L.

It is assumed that the LG units respond instantaneously to the system changes. The respective power injections of LG units have been incorporated in the power balance equations. The active power response of LG unit is P_{LG} whereas the reactive power response is Q_{LG}.

The describing function ($N(A)$) in the DB-ODE model of the OLTC can be derived as given by (04) [1], [6]. The amplitude of any sinusoidal input is A_s, where periodic OLTC limit cycles are assumed to be approximately sinusoidal. The condition associated with the occurrence of OLTC limit cycle phenomenon is given by (05), where the small signal model of the power system is given by (06). The limit cycle phenomenon under each operation is predicted using the proposed small signal model and the associated eigen value analysis. This is an extended version of the analysis done in [1].

$$N(A_s)=\begin{cases}1-\frac{2}{\pi}\left(sin^{-1}\left(\frac{DB}{2A_s}\right)+\frac{DB}{2A_s}\sqrt{1-\left(\frac{DB}{2A_s}\right)^2}\right) & \text{if } A_s>DB/2\\ 0 \quad \text{if } A_s<DB/2\end{cases} \tag{04}$$

$$\text{Condition for limit cycle phenomenon :}$$
$$G(j\omega)=(-)\left\{\frac{1}{N(A_s)}\right\}\quad\forall\; G(j\omega)=(-)G_n(j\omega)\times G_c(j\omega) \tag{05}$$

$G_n(s) \rightarrow$ transfer function of the power system model, which is derived from the state space model given by (06)
$G_c(s) \rightarrow$ transfer function of the ODE part of DBODE model

2) Case Study for a Two Bus System

The two bus system shown in Fig. 1 is used for investigating and analyzing OLTC limit cycle phenomenon under different system operational states.

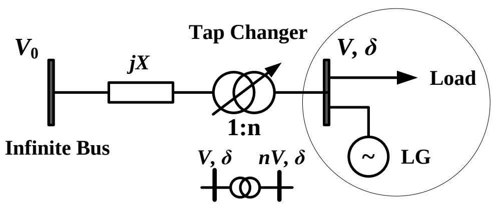

Fig. 1. Two bus system model.

The proposed mathematical model of the power system used for analyzing and predicting OLTC limit cycles is given below. The transformer equivalent impedance is jX [4].

System equations including dynamics:

$$\dot{x} = f(x, v), \quad g(x, v, P_{LG}, Q_{LG}, u) = 0$$

δ = voltage phasor angle, V = voltage magnitude

State space model:

$$\Delta\dot{x} = \left(\frac{\partial f}{\partial x}\right).\Delta x + \left(\frac{\partial f}{\partial v}\right).\Delta v$$

$$\left(\frac{\partial g}{\partial x}\right).\Delta x + \left(\frac{\partial g}{\partial v}\right).\Delta v + \left(\frac{\partial g}{\partial u}\right).\Delta u = 0$$

$$\Delta\dot{x} = (A).\Delta x + (B).\Delta n$$

$$\Delta v = (C).\Delta x + (D).\Delta n \qquad (06)$$

State matrix: $x = [x_p \quad x_q]^T$, Input matrix: $u = [n]$

n = tap ratio, Output matrix: $v = [V \quad \delta]^T$

$$A = \left(\frac{\partial f}{\partial x}\right) - \left(\frac{\partial f}{\partial v}\right)\left(\frac{\partial g}{\partial v}\right)^{-1}.\left(\frac{\partial g}{\partial x}\right), \quad C = (-).\left(\frac{\partial g}{\partial v}\right)^{-1}.\left(\frac{\partial g}{\partial x}\right)$$

$$B = (-).\left(\frac{\partial f}{\partial v}\right).\left(\frac{\partial g}{\partial v}\right)^{-1}.\left(\frac{\partial g}{\partial u}\right), \quad D = (-).\left(\frac{\partial g}{\partial v}\right)^{-1}.\left(\frac{\partial g}{\partial u}\right)$$

The existence of OLTC limit cycles in the presence of the LG unit has been tested for different load demand levels, and the key results of some example simulations are summarized below. The Nichols plots of both left and right hand side functions are used to solve the equation (05). The sample load and system data, used for simulation purposes, are P_0 = 106.8 MW, Q_0 = 43.2 MVAr, X = 0.10641 pu, α_s = 1, β_s = 0, α_t = 1, β_t = 4 and T_p = T_q= 60 s. The tap changer controller time delay (T) is 30 s. The simulated voltage change per tap operation is 0.0010 pu. The initial tap position of the OLTC is set at its nominal position for all simulations. The peak load demand is 96.005 MVA, where k_L = 1, 0.9, 0.8, 0.7, 0.6, 0.5, 0.4 and 0.3. The sending end bus voltage is 1.01 pu. Fig. 2 shows the respective Nichols plots for two bus system operation without LG unit (case-01). According to the Nichols plots (Gki, where i = 1, …, 8), it can be seen that the plots do not intersect the Nichols plot of –1/N(A) function for different values of k_L, which demonstrates that OLTC limit cycles do not exist for the test system without LG. The plot (GA), shown by the (orange color) vertical line, represents the Nichols plot of –1/N(A) function.

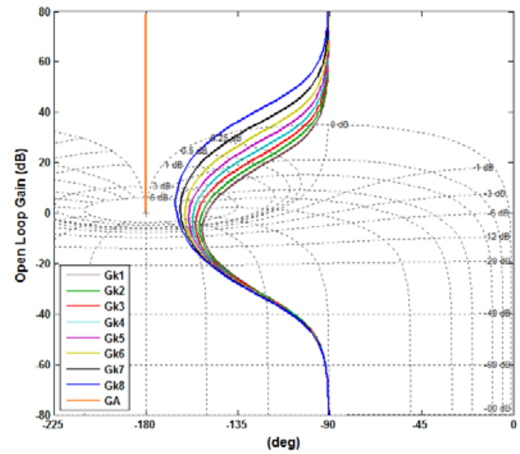

Fig. 2. Nichols plots of G(jω) function for different values of k_L in case of system operations without LG and Nichols plot of –1/N(A) (case-01).

According to the investigations, it can be seen that there can be OLTC limit cycles where active power generation level of the LG unit exceeds 26.5 MW and k_L = 0.3 as shown in Fig. 3 (case-02). Fig. 4 illustrates an example for OLTC limit cycles in real-time for the limit cycle phenomenon predicted in case-02 (Fig. 3). This is obtained by solving the first order differential equations of x-states which models the load recovery dynamics. In this case, the power output of the LG unit is assumed to be constant, where mechanical time delay of OLTC is assumed to be 6 s. The time domain simulation studies highlight the applicability of describing function method for predicting OLTC limit cycles in electric power systems with local generation, when utilizing a simplified version of the power system following network reduction methods.

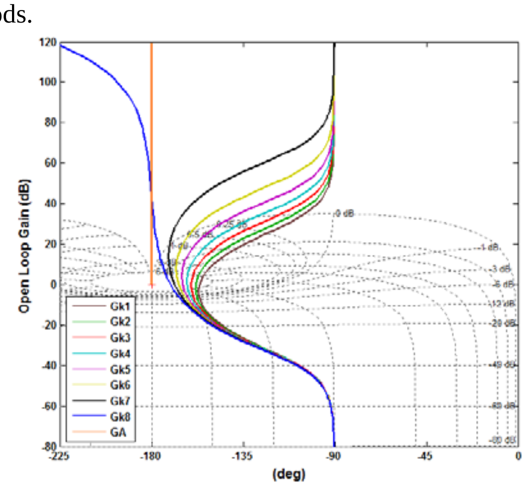

Fig. 3. Nichols plots of G(jω) function for different values of k_L in case of system operations with P_{LG} = 26.5 MW (case-02).

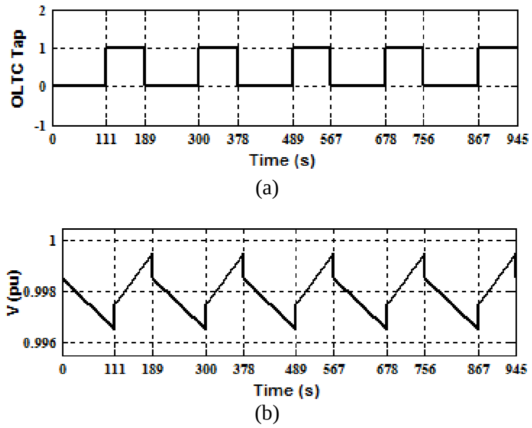

Fig. 4. Simulated (a) OLTC tap operations and (b) resultant voltage oscillations, which can occur due to OLTC limit cycle phenomenon predicted in case-02.

Fig. 5 shows that the OLTC limit cycles may recur frequently, if active power generation level of the LG unit exceeds 87.5 MW (case-03). It is indicative of the fact that compared to the system operation without LG, recurrence of OLTC limit cycles in the presence of a LG unit under any system operation can be high, as predicted. Also, after predicting for a particular load factor (k_L), the limit cycles may sustain for a longer time as shown in Fig. 4 especially under flat load profiles or load profiles with slow ramp variation. Therefore, an implementation strategy for mitigating OLTC limit cycles in the presence of LG units may be essential for networks with high penetration of LG.

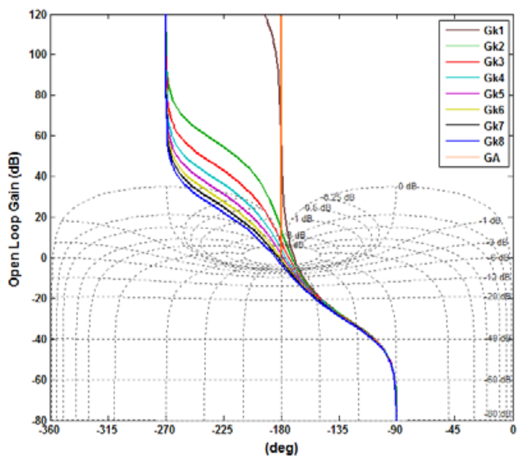

Fig. 5. Nichols plots of G(jω) function for different values of k_L in case of system operations with P_{LG} = 87.5 MW (case-03).

The reactive power support (export) of 13.5 MVAr by the LG unit in Fig. 1 can prevent the system from an oscillatory response, attributed to OLTC limit cycles, which can occur when the real power output of the LG unit is 26.5 MW and k_L = 0.3 as shown in Fig. 6 (case-04). It is indicative of the fact that OLTC limit cycles may be mitigated by considering degree of reactive power compensation and accordingly implementing a coordinated VAr management scheme in the system, comprising of Volt/VAr support by the LG unit.

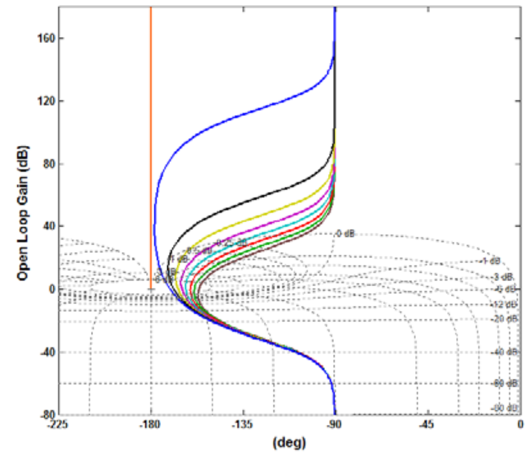

Fig. 6. Nichols plots of G(jω) function for different values of k_L in case of system operations with P_{LG} = 26.5 MW and Q_{LG} = 13.5 MVAr (case-04).

When the LG unit absorbs (import) reactive power of 9.6 MVAr (case-05), it is noted that the intersection point of the associated Nichols plots i.e., Gki (where k_L = 0.3) shifts downwards as shown in Fig. 7 along the GA curve to a lower open loop gain compared to the case-02. It means that the absorption of reactive power by the LG unit affects G(jω) function. Consequently, the amplitude of limit cycles is changed, but not the frequency. Moreover, shifting the curve below the point (0 dB, -180^0) can eliminate the limit cycle, but it may lead to instability of the closed loop system. In summary, it is clear that there would be a certain LG penetration level which can create OLTC limit cycles, and also which can mitigate OLTC limit cycles for each operational state of the system.

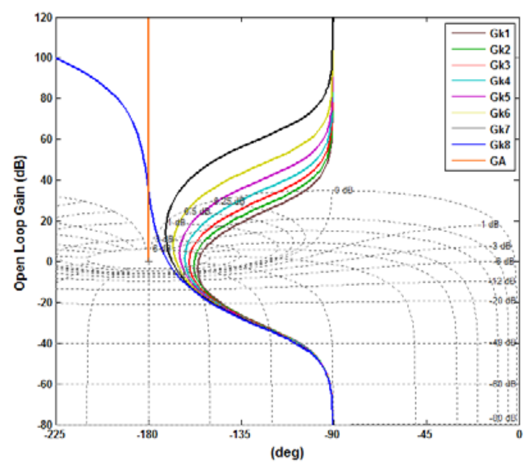

Fig. 7. Nichols plots of G(jω) function for different values of k_L in case of system operations with P_{LG} = 26.5 MW and Q_{LG} = – 9.6 MVAr (case-05).

According to the simulation case study discussed above, the rating of the system, S_{LG} /$S_{Load\text{-}Rated}$ and existence of OLTC limit cycles can be summarized as given in the Table I. It is indicative of the fact that implementing an OLTC limit cycle mitigation strategy in an alert-state would be more reliable as the occurrence of OLTC limit cycles also depends on the rating of the system, S_{LG} /$S_{Load\text{-}Rated}$ for an initial tap position of the OLTC.

TABLE I
RATING OF TWO BUS SYSTEM AND EXISTENCE (√=YES, ×=NO) OF OLTC LIMIT CYCLES

$S_{LG}/S_{Load\text{-}Rated}$	$k_L = 1.0$	$k_L = 0.9$	$k_L = 0.8$	$k_L = 0.7$
0 $S_{LG} = 0$ (No LG)	×	×	×	×
0.23 $Q_{LG} = 0$	×	×	×	×
0.24 $Q_{LG} =$ - 9.6 MVAr	×	×	×	×
0.26 $Q_{LG} =$13.5 MVAr	×	×	×	×
0.76 $Q_{LG} = 0$	√ Case-03	√ Case-03	√ Case-03	√ Case-03
$S_{LG}/S_{Load\text{-}Rated}$	$k_L = 0.6$	$k_L = 0.5$	$k_L = 0.4$	$k_L = 0.3$
0 $S_{LG} = 0$ (No LG)	×	×	×	×
0.23 $Q_{LG} = 0$	×	×	×	√ Case-02
0.24 $Q_{LG} =$ - 9.6 MVAr	×	×	×	√ Case-05
0.26 $Q_{LG} =$13.5 MVAr	×	×	×	×
0.76 $Q_{LG} = 0$	√ Case-03	√ Case-03	√ Case-03	√ Case-03

Finally, the eigen values of overall system state matrix for the above mentioned different operational states (case-01 to case-05) are derived and shown in Table II. The unstable scenarios with OLTC limit cycles, where at least one of the eigen values has a positive real part are highlighted. The results of the eigen value analysis are very much in agreement with the results obtained using the describing function method, which has been used for predicting the existence of OLTC limit cycles. Moreover, a modal analysis can be done using the proposed small signal model in order to identify the oscillatory modes referred to OLTC limit cycle instability especially in case of long term voltage collapse phenomenon; which is out of the scope of this paper.

TABLE II
RESULTS OF EIGEN VALUE ANALYSIS FOR THE TWO BUS SYSTEM OPERATION

Case Study	$k_L = 1.0$	$k_L = 0.9$	$k_L = 0.8$	$k_L = 0.7$
Case-01	- 0.0010 - 0.0167	- 0.0009 - 0.0167	- 0.0008 - 0.0167	- 0.0007 - 0.0167
Case-02	- 0.0007 - 0.0167	- 0.0006 - 0.0167	- 0.0005 - 0.0167	- 0.0004 - 0.0167
Case-03	+ 0.0000 - 0.0167	+ 0.0001 - 0.0167	+ 0.0002 - 0.0167	+ 0.0003 - 0.0167
Case-04	- 0.0007 - 0.0167	- 0.0006 - 0.0167	- 0.0005 - 0.0167	- 0.0004 - 0.0167
Case-05	- 0.0007 - 0.0167	- 0.0006 - 0.0167	- 0.0005 - 0.0167	- 0.0004 - 0.0167
Case Study	$k_L = 0.6$	$k_L = 0.5$	$k_L = 0.4$	$k_L = 0.3$
Case-01	- 0.0006 - 0.0167	- 0.0005 - 0.0167	- 0.0004 - 0.0167	- 0.0003 - 0.0167
Case-02	- 0.0003 - 0.0167	- 0.0002 - 0.0167	- 0.0001 - 0.0167	+ 0.00000 - 0.0167
Case-03	+ 0.0004 - 0.0167	+ 0.0005 - 0.0167	+ 0.0006 - 0.0167	+ 0.0007 - 0.0167
Case-04	- 0.0003 - 0.0167	- 0.0002 - 0.0167	- 0.0001 - 0.0167	- 0.0000 - 0.0167
Case-05	- 0.0003 - 0.0167	- 0.0002 - 0.0167	- 0.0001 - 0.0167	+ 0.00001 - 0.0167

B. Case Study for a Multi Bus System

In this case study, OLTC limit cycle phenomenon is investigated and analyzed for a multi-bus system, as shown in Fig. 8, for different system operational states, and one of the simulated cases is presented in this paper. The describing function analysis and eigen value analysis are carried out, and compared for the multi bus system in order to further test the applicability of the mathematical model derived under Section II-*A* for predicting the OLTC limit cycles. Multi-bus system of Fig. 8 is derived from [7] and modified by adding load dynamics, control data and the line data (i.e., $R_5 = 0.00192$ pu and $X_5 = 0.04256$ pu) related to connecting the LG unit.

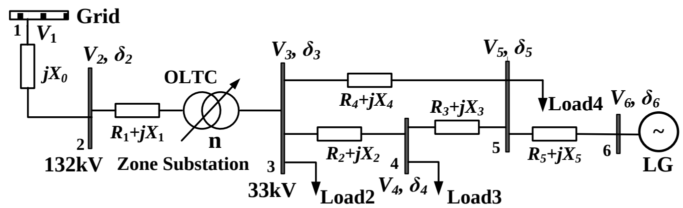

Fig. 8. Multi bus system model with single OLTC.

The bus voltage magnitudes are V_0, V_1, V_2, V_3, V_4 and V_5 form grid to the LG bus, where the voltage phasor angles are *zero*, δ_1, δ_2, δ_3, δ_4 and δ_5, respectively. The tap ratio of the substation transformer equipped with OLTC is n for particular instance of time. The line impedances are jX_0, (R_2+jX_2), (R_3+jX_3), (R_4+jX_4) and (R_5+jX_5) from grid to the LG bus, respectively. The substation transformer equivalent impedance is (R_1+jX_1) [4]. The respective admittance values are denoted using Y, where their phasor angles are denoted using γ. The small signal model of the multi bus power system is given by (07). If there is a capacitor (CB) in the system, it can be modeled using its susceptance value, B as shown below.

System equations including dynamics:

$$\dot{x} = f(x, v), \quad g(x, v, P_{LG}, Q_{LG}, B, u) = 0, \quad Q_{CB} = B.V^2$$

From π - equivalent model of OLTC transformer:

$$Y_{32} = Y_{23} = \left(\frac{Y_t}{n}\right), \quad Y_{33} = \left(\frac{1-n}{n^2}\right).Y_t, \quad Y_{22} = \left(\frac{n-1}{n}\right).Y_t$$

$$\gamma_{22} = \gamma_{32} = \gamma_{33} \equiv \gamma_{y_t}$$

State space model:

$$\Delta\dot{x} = \left(\frac{\partial f}{\partial x}\right).\Delta x + \left(\frac{\partial f}{\partial v}\right).\Delta v$$

$$\left(\frac{\partial g}{\partial x}\right).\Delta x + \left(\frac{\partial g}{\partial v}\right).\Delta v + \left(\frac{\partial g}{\partial u}\right).\Delta u = 0$$

$$\Delta\dot{x} = (A_1).\Delta x + (B_1).\Delta n$$
$$\Delta v = (C_1).\Delta x + (D_1).\Delta n \qquad (07)$$

State matrix: $x = \left[x_{p3} \quad x_{q3} \quad x_{p4} \quad x_{q4} \quad x_{p5} \quad x_{q5}\right]^T$

Input matrix: $u = [n]^T$

Output matrix: $v = [V_3 \quad V_4 \quad V_5 \quad \delta_3 \quad \delta_4 \quad \delta_5]^T$

$$A_1 = \left(\frac{\partial f}{\partial x}\right) - \left(\frac{\partial f}{\partial v}\right) \cdot \left(\frac{\partial g}{\partial v}\right)^{-1} \cdot \left(\frac{\partial g}{\partial x}\right), \qquad C_1 = (-) \cdot \left(\frac{\partial g}{\partial v}\right)^{-1} \cdot \left(\frac{\partial g}{\partial x}\right)$$

$$B_1 = (-) \cdot \left(\frac{\partial f}{\partial v}\right) \cdot \left(\frac{\partial g}{\partial v}\right)^{-1} \cdot \left(\frac{\partial g}{\partial u}\right), \qquad D_1 = (-) \cdot \left(\frac{\partial g}{\partial v}\right)^{-1} \cdot \left(\frac{\partial g}{\partial u}\right)$$

For the tap changer model, input is the transformer secondary bus voltage magnitude, V_3 whereas output is the tap ratio, n. The OLTC limit cycles can be predicted as shown in Fig. 9, where the simulated load and system data are as below: total P_0 = 94.0 MW, total Q_0 = 21.0 MVAr, $\alpha_s = \beta_s = 1$, $\alpha_t = 2$, $\beta_t = 4$, T_p = 120 s, T_q= 60 s and OLTC controller time delay, T = 30 s. The total active and reactive power outputs (export) by the LG unit are 34.6 MW and 5.3 MVAr, respectively. Initial tap position of OLTC is '1' in the direction of increasing voltage, where taps are incorporated in the primary winding of the substation transformer. The total peak load demand is around 90.0 MVA, where k_L = 0.85 and the grid voltage is 1.0 pu. In this case, the rating of the system, $S_{LG} / S_{Load\text{-}Rated}$ is 0.36.

The eigen values derived using overall system state matrix with the VAr support by the LG unit are shown in Table III. They are indicative of the fact that OLTC limit cycles can also exist with the LG unit operating in voltage control mode, especially when the control action of the LG unit has not been coordinated with the operation of other voltage control devices. Also, this simulation shows the applicability and suitability of the proposed eigen value analysis for predicting OLTC limit cycles in multi bus systems. Therefore, the proposed strategy in section-III for mitigating OLTC limit cycles is mainly based on the proposed mathematical model and the associated eigen value analysis which can be used for predicting OLTC limit cycles in electricity networks with LG.

TABLE III
RESULTS OF EIGEN VALUE ANALYSIS FOR THE MULTI BUS SYSTEM OPERATION WITH VAR SUPPORT OF THE LG UNIT

+ 0.0010 + j0.0008	+ 0.0010 - j0.0008	- 0.0186	- 0.0174	- 0.0078	- 0.0081

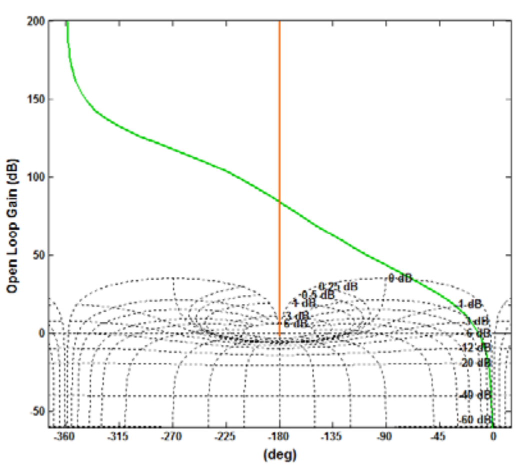

Fig. 9. Nichols plots of G(jω) for an existence of OLTC limit cycles in the multi bus system when k_L = 0.85, P_{LG} = 34.6 MW and Q_{LG} = 5.3 MVAr.

III. PROPOSED CONTROL STRATEGY FOR MITIGATING OLTC LIMIT CYCLES IN PRESENCE OF LOCAL GENERATION

From power system control perspective, the system-operating conditions are normally classified into five states such as normal, alert, emergency, extreme emergency and restorative [8]. In the proposed strategy for mitigating OLTC limit cycles, the control transition is between normal and the alert states. The system enters the alert-state form the normal-state, if existence of OLTC limit cycles is predicted. Then, the preventive control action based on the proposed control strategy is activated to mitigate the OLTC limit cycles while controlling the system voltage. Since, (a) the objectives of normal-state conventional voltage control can be different and incorporating those objectives with mitigating OLTC limit cycles may not always be effective and (b) the possibility of occurring OLTC limit cycles also dependant on the rating of the system, $S_{LG} / S_{Load\text{-}Rated}$; transition based voltage control is used in the paper. This is a key feature of the proposed control strategy applicable to power systems embedded with LG units, because normal-state voltage control is not an easy task in presence of local generation [9].

The system load level, penetration of LG, degree of reactive power compensation and the load-voltage dependency are identified as the key parameters for mitigating the OLTC limit cycles. On the other hand, it may not be possible to avoid limit cycle behavior under certain system operating conditions simply by retuning the OLTC control parameters. For example, an increase of the DB size will only increase the amplitude of a limit cycle but will not remove it. Similarly, the different time delays in the OLTC control system have no influence on the existence of limit cycles, only on the amplitude and period time. The only parameters which can affect the existence of limit cycles are load and network parameters [1], [3]. In this paper, the level of reactive power compensation is used as the key parameter for mitigating OLTC limit cycles in the electricity networks embedded with LG; and the proposed mitigating strategy is developed based on dynamic VAr management in the network using reactive power capability of available LG units and shunt CBs. Hence, the functionality of the proposed control strategy is dependent on the reactive power capability of LG units and the ratings of CBs.

Also, it is proposed to embed the proposed control module in a centralized voltage control scheme in terms of additional hardware and software elements for updated distribution management system (DMS) operation, thereby ensuring effective voltage control. With the aid of modern smart-grid infrastructure and advanced DMS, the control execution can be done in real-time by effectively and efficiently updating the inputs, processing the algorithm and generating the output control information. Hence, there cannot be specific obstacles associated with the implementation of the proposed control strategy to mitigate OLTC limit cycles in a power system with LG, under smart grid infrastructure and advanced DMS functionality. The enhancements required for smart grid applications and improvements required for DMS functionalities are being developed.

A. Proposed Strategy

This is mainly based on exploring the impact of degree of reactive power compensation on OLTC limit cycles, and accordingly coordinated VAr control in the system using reactive power capabilities of LG units and CBs for avoiding the conditions which have to be satisfied for the existence of OLTC limit cycles. From (07) and for particular system operation, it can be seen that the *A*-matrix is also a function of nodal voltage magnitudes and phase angles as given by (08).

$$A = \left(\frac{\partial f}{\partial x}\right) - \left(\frac{\partial f}{\partial v}\right) \cdot \left(\frac{\partial g}{\partial v}\right)^{-1} \cdot \left(\frac{\partial g}{\partial x}\right)$$
$$\left(\frac{\partial f}{\partial v}\right) = f(V), \quad \left(\frac{\partial g}{\partial v}\right) = f(V,\, \delta) \quad \rightarrow \quad A = f(V,\, \delta) \qquad (08)$$

Hence, by means of voltage control through coordinated VAr management in the system, a stable system operation without system oscillations, typically induced by OLTC limit cycles, can also be achieved. Accordingly, the proposed mitigation strategy is developed. The step-by-step algorithm of the proposed strategy is outlined below.

Step-01: From the on-line measurements and information sent by DMS, the control module is executed.

Step-02: For the current state of the system, the overall system state matrix is updated and the respective eigen values are derived.

Step-03: If all the eigen values have negative real part, the normal-state voltage control module is enacted.

Step-04: If at least one eigen value has a positive real part, the alert-state voltage control module is enacted.

Step-05: The sensitivity matrix, S_M given by (09) is derived with the aid of analytical strategy proposed by authors in [10]. The sensitivity values for VAr support by the LG unit and the CB are S_{MQLG} and S_{MQCB}, respectively, where ΔV is voltage deviation for small change of the LG unit's reactive power (import/export), ΔQ_{LG} and CB's reactive power (export), ΔQ_{CB}.

$$\Delta V = \left[S_{MQLG} \;\vdots\; S_{MQCB}\right] \cdot \begin{bmatrix} \Delta Q_{LG} \\ \Delta Q_{CB} \end{bmatrix}, \qquad S_M = \left[S_{MQLG} \;\vdots\; S_{MQCB}\right] \qquad (09)$$

Step-06: The operational sequence of VAr support devices (i.e. LG units and CBs) which are going to be utilized for coordinated VAr support is determined based on the amount of voltage correction offered by each device (i.e. maximum to minimum in order), which is derived using two parameters. They are (i) the sensitivity values derived in Step-05, and (ii) capability of the VAr devices for supporting the system voltage. The generalized sequence in terms of time delays, T is given by (10). The control logic adopted for local control of CB is given by (11); where t, V_{CB}, SCB_t, V_{ON} and V_{OFF} denote time, CB target point voltage, switching position, switching *ON* voltage and switching *OFF* voltage, respectively [11]. The local controls for LG unit VAr control are detailed in [12], where local control of OLTCs is detailed in [9].

$$T_{LG-larger} < \ldots < T_{LG-smaller} < T_{CB-larger} < \ldots < T_{CB-smaller}$$
$$< OLTC_{upstream} < \ldots < OLTC_{downstream} \qquad (10)$$

$$SCB(t+1) = \begin{cases} ON & \text{if } SCB_t = OFF \text{ and } V_{CB} < V_{ON} \\ SCB_t & \text{if } V_{ON} \le V_{CB} \le V_{OFF} \\ OFF & \text{if } SCB_t = ON \text{ and } V_{CB} > V_{OFF} \end{cases} \qquad (11)$$

Step-07: The new VAr reference values for selected VAr support devices (i.e., LG units and CBs) are identified subject to operational sequence derived under Step-06, system constraints and capability limits of the LG units [13] and CBs, where objective is to ensure stable system operation without OLTC limit cycles and maintain the system voltage within stipulated limits.

Step-08: The updated VAr reference values are assigned for local controllers of the LG units and CBs.

Step-09: The OLTC local controllers are enabled.

Step-10: For the subsequent instances of time (i.e., $t = t + 1$), repeat the procedure starting from Step-01.

Flow chart of the proposed voltage control algorithm prior to enacting OLTC tap operations is shown in Fig. 10.

The voltage control strategy proposed in [9] can be used for normal-state voltage control in conjunction with the proposed strategy of mitigating OLTC limit cycles. It is an online voltage control strategy which is designed and tested for correcting the system voltage with control-coordination ascertaining voltage support by LG units in the system. Also, it ensures prioritized voltage support operation of LG units and the voltage regulating devices, and aids in blocking simultaneous operations, thereby minimizing the total tap operations. However, even with this voltage control, there could be a possibility of recurrence of OLTC limit cycles in presence of LG; since there is not any mechanism to avoid OLTC limit cycles.

Design of the proposed control module contains the embedded mathematical model of the power system, model of the proposed control logic, search engine and the decision making control layer for enacting the VAr controllers of LG units, CBs and the tap operations of OLTCs. The search engine based on the proposed control algorithm, as detailed in the flow chart in Fig. 10, is adopted in order to determine the control parameters of LG units and CBs.

The practical implementation strategy for proposed control is outlined in Fig. 11 for an example electricity network with cascaded OLTCs. The proposed control modules are embedded in a grid substation centered DMS for on-line voltage control. The details on substation centered DMSs can be found from [14], [15]. The control panels of LG units and voltage regulating devices are proposed to be equipped with supervisory control and data acquisition (SCADA) facilities.

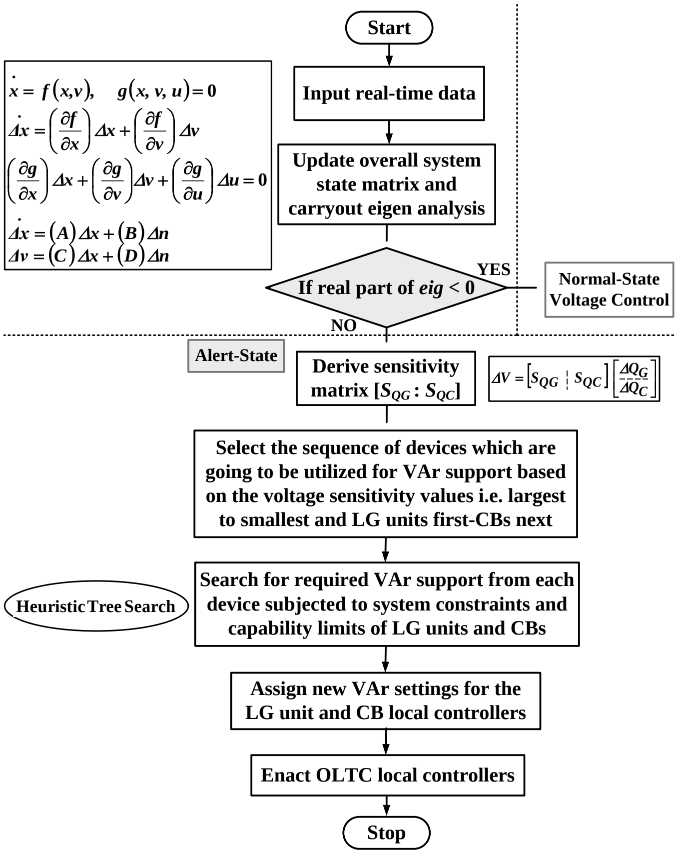

Fig. 10. Flow chart of the proposed voltage control algorithm with capability of mitigating OLTC limit cycles.

The proposed control module is implemented to act as a separate module embedded in to a standard distribution DMS, and it only utilizes information from the DMS where control functions are independent from the outputs of the DMS. Also, substation centered advanced DMS schemes are capable of utilizing user-defined algorithms and customized software/hardware to determine best operating settings for voltage control devices and LG units in real-time [9], [15]. It is to be noted that no major modifications are required to be implemented in the DMS for adopting the proposed voltage control scheme.

The proposed strategy is tested using different case studies, and performance analysis of the algorithm under different system operating conditions (i.e. states) is given below.

B. Test Case Study-1

1) Test Results

In this case study, the multi-bus test system shown in Fig. 8 is considered. Data of some of the simulated operating points where OLTC limit cycles are predicted, are summarized in Table IV. For the OLTC, 32 taps are assumed with +/- 0.1 pu voltage correction capacity. The proposed eigen value analysis which predicts OLTC limit cycles in each state is performed according to Step-01 to Step-03 of the proposed control strategy detailed in Section III-*A*. Results of the eigen value analysis are shown in Table V.

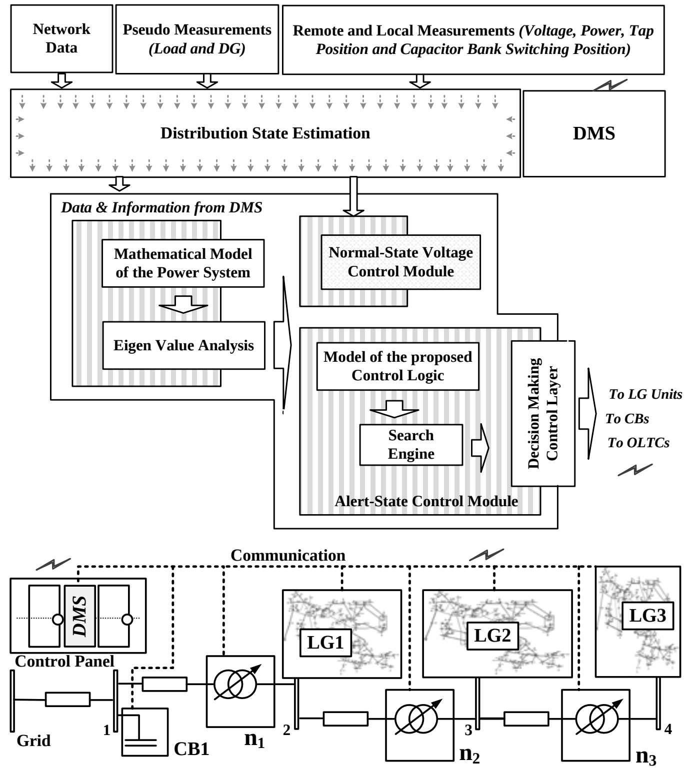

Fig. 11. Topology of the on-line implementation of proposed control strategy for an electricity network with cascaded OLTCs, CB and multiple LG units.

TABLE IV
SIMULATED TEST DATA FOR THE MULTI BUS SYSTEM WITH SINGLE OLTC

Simulated State-01	Simulated State-02	Simulated State-03
k_L = 1.00	k_L = 0.60	k_L = 0.85
P_L = 38.0 MW	P_L = 25.3 MW	P_L = 34.6 MW
Q_L = 0 MVAr	Q_L = (-) 2.3 MVAr	Q_L = (+) 5.3 MVAr
n_{start} = 0.98750	n_{start} = 1.0000	n_{start} = 0.99375

TABLE V
RESULTS OF EIGEN VALUE ANALYSIS UNDER STEP-03 OF THE PROPOSED CONTROL FOR THE MULTI BUS SYSTEM WITH SINGLE OLTC

Simulated State-01	Simulated State-02	Simulated State-03
Bus Voltages/(pu)	Bus Voltages/(pu)	Bus Voltages/(pu)
V_1= 1.000 V_2= 0.984 V_3= 0.970 V_4= 0.963 V_5= 0.971 V_6= 0.972	V_1= 1.000 V_2= 0.989 V_3= 0.972 V_4= 0.966 V_5= 0.971 V_6= 0.970	V_1= 1.000 V_2= 0.990 V_3= 0.981 V_4= 0.979 V_5= 0.997 V_6= 1.000
Eigen Values	Eigen Values	Eigen Values
+ 0.0044	+ 0.0003 + *j*0.0033	+ 0.0010 + *j*0.0008
- 0.0188	+ 0.0003 - *j*0.0033	+ 0.0010 - *j*0.0008
- 0.0174	- 0.0180	- 0.0186
- 0.0011	- 0.0171	- 0.0174
- 0.0078	- 0.0079	- 0.0078
- 0.0081	- 0.0082	- 0.0081

Subsequently, as in the Step-04 of the proposed algorithm, voltage control is moved to an alert state if OLTC limit cycle is predicted. Accordingly, as in the Step-05, the sensitivity matrix, S_M is derived. The sensitivity matrix for each state (i.e. $S_{M(i)}$, i=01 to 03) where OLTC limit cycles are predicted is shown in (12). The busses of the test system are counted from the substation-grid (slack bus) as shown in the Fig. 8.

$$S_{M(01)} = \begin{bmatrix} 0.0762 \\ 0.1969 \\ 0.2748 \\ 0.4296 \\ 0.4733 \end{bmatrix}, \quad S_{M(02)} = \begin{bmatrix} 0.0733 \\ 0.1902 \\ 0.2671 \\ 0.4228 \\ 0.4670 \end{bmatrix}, \quad S_{M(03)} = \begin{bmatrix} 0.0706 \\ 0.1828 \\ 0.2556 \\ 0.4011 \\ 0.4426 \end{bmatrix} \tag{12}$$

Next, the sequence of VAr support devices which are going to be utilized for coordinated VAr support is determined as in Step-06 (in this case only LG unit). According to Step-07, the new VAr reference value for LG unit is derived. The simulation results are shown in Table VI. The eigen value analysis is also performed with the new VAr settings in order to compare the results in respective pre alert-state control (Table V). Next, only in the alert-states, the updated VAr reference values are assigned to the local controller of LG unit according to Step-08, where the OLTC local controller is enacted according to Step-09 of the proposed algorithm. In other states of the system, the voltage control is in normal-state after the Step-03 of the proposed control. In the Step-10, next control-state is counted and enacted.

TABLE VI
VAR REFERENCE VALUES, BUS VOLTAGES AND EIGEN VALUES UNDER PROPOSED CONTROL FOR THE MULTI BUS SYSTEM WITH SINGLE OLTC

State-01	State-02	State-03
VAr Reference the LG Unit	VAr Reference the LG Unit	VAr Reference for the LG Unit
4.7 MVAr	1.8 MVAr	0.50 MVAr
Bus Voltages/(pu)	Bus Voltages/(pu)	Bus Voltages/(pu)
V_1= 1.000 V_2= 0.987 V_3= 0.979 V_4= 0.975 V_5= 0.991 V_6= 0.994	V_1= 1.000 V_2= 0.992 V_3= 0.980 V_4= 0.977 V_5= 0.988 V_6= 0.989	V_1= 1.000 V_2= 0.987 V_3= 0.979 V_4= 0.977 V_5= 0.987 V_6= 0.988
Eigen Values	Eigen Values	Eigen Values
- 0.0189	- 0.0000 + j0.0036	- 0.0003
- 0.0189	- 0.0000 - j0.0036	- 0.0001
- 0.0089	- 0.0181	- 0.0185
- 0.0008	- 0.0172	- 0.0173
- 0.0078	- 0.0079	- 0.0078
- 0.0081	- 0.0082	- 0.0081

C. Test Case Study-2

1) Test Results

In this case study, a MV test system with cascaded OLTCs, CB and multiple LG units is considered. This sample test system is operated with 3 OLTCs, 3 LG units and a CB for Volt/VAr correction, and its topological model is given in Fig. 12. In this test system, OLTC limit cycles can be induced not only due to interaction among load dynamics, OLTC control and the power generated by LG units, but also due to interaction of CB.

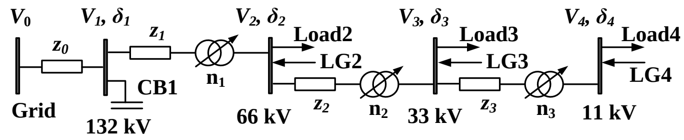

Fig. 12. Multi bus system model with cascaded OLTCs.

The bus voltage magnitudes are V_0, V_1, V_2, V_3, and V_4 from grid to the 11 kV bus, where the voltage phasor angles are zero, δ_1, δ_2, δ_3, and δ_4, respectively. The tap ratios of the substation transformers equipped with OLTC are n_1, n_2, and n_3, respectively for particular instance of time. The line impedances are z_0, z_1, z_2, and z_3 including the respective transformer equivalent impedances [4] from grid to the 11 kV bus. The small signal model of the system can be derived similar to (07) and defining state, input and output matrices as given by (14).

$$\begin{aligned} &\text{State matrix}: x = [x_{p2} \quad x_{q2} \quad x_{p3} \quad x_{q3} \quad x_{p4} \quad x_{q4}]^T \\ &\text{Input matrix}: u = [n_1 \quad n_2 \quad n_3]^T \\ &\text{Output matrix}: v = [V_2 \quad V_3 \quad V_4 \quad \delta_2 \quad \delta_3 \quad \delta_4]^T \end{aligned} \tag{13}$$

In this test case study, different system operational states are simulated and one of the cases is presented. In this state (at t=t), a possibility of limit cycles in OLTC (n_1) and OLTC (n_2) is predicted according to Step-01 to Step-03 of the proposed control algorithm detailed earlier in Section III-*A*. The results of the proposed eigen value analysis which predicts OLTC limit cycles are shown in Table VII. The predicted OLTC limit cycles may or may not be sustained in case of cascaded OLTCs, because of the hunting phenomenon [1]. However, enacting a mitigating strategy would be essential in a realistic network, as emulated for the above test system, with a significant penetration of local generation; because there is a higher possibility of sustaining the predicted OLTC limit cycle phenomena due to intermittency in power outputs of the LG units and associated changes in system dynamics.

The simulated load scale factors for loads 2, 3, and 4 are k_{L2} = 0.8, k_{L3} = 0.9, and k_{L4} = 0.9 respectively. The total peak load demands for loads 2, 3, and 4 are 80 MVA, 12.800 MVA and 3.128 MVA, respectively; where P_{02} = 86.4 MW, Q_{02} (export) = 41.8454 MVAr, P_{03} = 13.824 MW, Q_{03} (export) = 6.6953 MVAr, P_{04} = 3.456 MW and Q_{04} (export) = 1.6738 MVAr. The rating of the CB is 40 MVAr and simulated VAr support is 20 MVAr. The simulated initial tap positions of OLTC, n_1, n_2 and n_3, are 2, 4 and 4 respectively in the direction of increasing voltage, where the controller time delays are 30 s, 45 s and 60 s respectively. The simulated active and reactive power generations of LG1, LG2 and LG3 units are (33.000

MW, 9.300 MVAr (export)), (6.500 MW, 0 MVAr) and (1.600 MW, 0 MVAr), respectively. The simulated load parameters of loads 2, 3 and 4 are (α_{s2} = 1.5, β_{s2} = 4.5, α_{t2} = 8, β_{t2} = 3, T_{p2} = 174 s, T_{q2} = 84 s), (α_{s3} = 2.5, β_{s3} = 5.5, α_{t3} = 4, β_{t3} = 1.5, T_{p3} = 201 s, T_{q3} = 48 s) and (α_{s4} = 1, β_{s4} = 3.5, α_{t4} = 6, β_{t4} = 2, T_{p4} = 121 s, T_{q4} = 64 s), respectively. The line data as shown in Fig. 13 are z_0 = (0.0129 + j0.0550) pu, z_1 = (0.0011 + j0.0950) pu, z_2 = (0.1510 + j0.6721) pu, and z_3 = (0.1989 + j2.6565) pu, respectively. The simulated grid voltage is 1.010 pu. The voltages at buses 1, 2, 3, and 4 are 1.002 pu, 0.990 pu, 0.964 pu and 0.951 pu, respectively.

Subsequently (as in the Step-04 of the proposed algorithm), voltage control is moved to an alert-state. According to Step-05, the sensitivity matrix, S_M is derived. The sensitivity matrix where OLTC limit cycles are predicted is shown in (14). Next, the sequence of VAr support devices (i.e., LG units and CB) which are going to be utilized for coordinated VAr support is determined as in Step-06, and it is shown in (15). According to Step-07, the new VAr reference values (export) for selected VAr support devices are derived and they are 10.200 MVAr, 1.900 MVAr, 0.300 MVAr and 25 MVAr, for LG2, LG3, LG4 and CB respectively. In this case, the voltages at buses 1, 2, 3, and 4 are 1.007 pu, 0.998 pu, 0.988 pu and 0.985 pu, respectively. The results of the eigen value analysis are shown in Table VII. Finally, the updated VAr reference values are assigned to the local controllers of the LG units and CB, and the OLTC local controllers are enabled according to Step-08 and Step-09, respectively of the proposed algorithm. For the subsequent instance of time, t=t +1, the procedure is repeated starting from Step-01.

$$S_M = \left[S_{MQLG2} \mid S_{MQLG3} \mid S_{MQLG4} \mid S_{MQCB1} \right]$$

$$S_M = \begin{bmatrix} 0.0690 & 0.0639 & 0.0578 & 0.0548 \\ 0.1893 & 0.1753 & 0.1591 & 0.0571 \\ 0.9873 & 0.9144 & 0.1727 & 0.0620 \\ 0.9995 & 0.9770 & 0.1845 & 0.0662 \end{bmatrix} \quad (14)$$

$$T_{LG2} < T_{LG3} < T_{LG4} < T_{CB1} < OLTC_1 < OLTC_2 < OLTC_3 \quad (15)$$

TABLE VII
THE RESULTS OF EIGEN VALUE ANALYSIS UNDER PRE ALERT-STATE AND ALERT-STATE FOR THE MULTI BUS SYSTEM WITH CASCADED OLTCS

Pre Alert-State					
+ 0.0140	- 0.0227	- 0.0139	- 0.0086	- 0.0010	- 0.0036
Alert-State					
- 0.0097	- 0.0200	-0.0094+ j0.0023	-0.0094 - j0.0023	-0.0023	- 0.0037

According to the above analyses and simulation case studies, it is very clear that the proposed methodology of mitigating OLTC limit cycles is applicable to any network, after carefully simplifying and modeling the system and the associated control logic, compatible to implement the proposed algorithm. The linear state space modeling of complex and large electric systems is referred to [16], [17].

IV. CONCLUSION

This paper presents an analysis detailing OLTC limit cycle phenomena and explores a mitigation strategy in the presence of local generation units. The OLTC limit cycles normally occur in electricity networks due to interactions among load dynamics and OLTC controls, resulting into sustained long term oscillations. The OLTC limit cycles due to interactions among different loads, OLTC controls and local generation operation have been thoroughly investigated in this paper. The level of reactive power compensation is used as one of the key parameters for mitigating OLTC limit cycles. The proposed mitigating strategy is developed based on dynamic VAr management in the network using reactive power capability of LG units and capacitor banks. The main contributions of this paper are (a) development of small signal model and application of describing function method for analyzing OLTC limit cycles for power systems embedded with LG, (b) investigation and analysis of OLTC limit cycle phenomenon in presence of LG equipped with voltage control capabilities, and (c) development of a new strategy for mitigating OLTC limit cycles in presence of LG, which is designed for alert state voltage control in conjunction with conventional voltage control. On-line application of the proposed control strategy will effectively mitigate the sustained oscillations attributed to OLTC limit cycles in networks embedded with LG.

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