Normal operation and reverse action of on-load tap changing transformer with its effect on voltage stability

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ABSTRACT

As electrical grids have expanded significantly, so too has the load on network buses. This, however, causes voltage drops to occur at the load side of the grid. A voltage drop causes a system to become unstable, increases its power loss, and reduces the amount of power that it transfers before finally leading to a collapse. An on-load tap changing (OLTC) transformer can be used to prevent the negative effects of an increased load by restoring the load voltage to its base value when sudden disturbances occur in the source. However, incorrect OLTC placement can cause the system to become unstable and cause collapse. This is referred to as the reverse action phenomenon of an OLTC. Therefore, this present study examined improving the ability of an OLTC to increase system stability and prevent collapse. A simple radial power distribution system was modelled in MATLAB. The results indicate that the proposed model can increase system stability and prevent collapse.

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1. INTRODUCTION

Many aspects of our day to day lives rely on the electricity produced by the multiple power systems scattered all over the country. However, voltage stability is one of the biggest problems that these power networks face [1]. Therefore, many studies have examined voltage stability problems as they are important [2], [3].

Voltage stability of any power system is, the ability of that system to restore its voltage to an acceptable and normal range after a sudden disturbance occurs [4]. A system goes into voltage instability mode when a disturbance leads to a progressive or uncontrollable drop in voltage [5]. As voltage instability is a dynamic process, the real power-bus voltage (P-V) curve can be used to obtain a better understanding of voltage analyses in stability studies [6]. The transferred power loss and the voltage drop are involved in system voltage instability [7]. Voltage drops occur due to heavy loads or large disturbances and causes an increase in the system currents. Thus, the grid equipment and the power system devises can damaged [8]. If a voltage drop is treated at the right moment, the system will restore to stability, otherwise it will collapse [9]. The collapse will cause a huge financial loss for the industrial sector [10].

Many researchers over the past years, deals with the voltage instability problem and found many ways to control the systems voltage. Flexible AC transmission systems (FACTS) [11], capacitors [12], distribution generators (DG) [13], and on-load tap changing (OLTC) transformers [14] are examples of devices that can be used to stabilize and maintain the voltage of a system at the desired level after a heavy load or source drop. Of these devices, OLTC transformers are most commonly used [15]. An OLTC is a critical component that is suitable for systems where the power flows in just one direction [16]. Furthermore, OLTCs are more widely used than FACTS or shunt capacitors as the latter two only affect the bus that they are used on [17]. For example, if a FACTS or shunt capacitor is used on a weak bus, only the voltage of that bus will be affected. An OLTC transformer, on the other hand, improves the voltage of the weak bus and that of the other buses as well [18]. Transfer power losses [19], [20] and the operating costs decrease when voltage drops are regulated and restored to its rated value [21].

An OLTC regulates the voltage of the secondary side of the transformer to ensure that it is equal or close to the base voltage of the system. The regulation method is done by continuous monitoring to the transformer output voltage by the control unit. The control unit compares the output voltage with the reference voltage and takes the decision to change the coil tap in light of the amount of voltage drop. This action may take several seconds depending on the controller delay time and tap changer switching time [22].

An OLTC regulates voltage by controlling the number of winding turns and, therefore, the turn ratio. This regulating process is very useful for treating voltage drops in a system. However, when a reverse action occurs, the OLTC becomes the cause of a collapse. This occurs because the OLTC increases the turn ratio, thereby decreasing the voltage [23]. However, OLTCs can cause a collapse when the reverse action phenomenon occurs [24]. A reverse action occurs when the system is heavy loaded and the load impedance of a simple radial power system is less than the impedance of the transmission line multiplied by the turn ratio [25].

In this work, the transformer turn-ratio boundaries and its effect on the system voltage stability will found mathematically as equations from the equivalent circuit of a simple radial power system in terms of the transmission line impedance and load impedance. A MATLAB model for the power system will be simulated to prove the accuracy of the equations and their activeness. A few methods to improve the OLTC performances will suggested and simulated to show their effect on the OLTC performances.

2. METHOD

In this work, the relation between load impedance (Z_L), transmission line impedance (Z_{TL}), and transformer turns ratio (n) will be derived and the effect of n on voltage stability and its boundaries will be explained. A chain of events will be used to explain the phenomenon of reverse action. In addition, several methods to improve OLTC performances will be discussed. This present study used P-V curves as an indicator of system stability and the location of voltage collapses.

2.1. OLTC and voltage stability limitations analyses

The system seen in Figure 1 was used to determine the voltage stability regained with an OLTC. The simple model consists of one generator (E), a transmission line (Z_{TL}), an OLTC, and an increasing load (Z_L). The system in Figure 1 can represent an equivalent circuit for a huge power system.

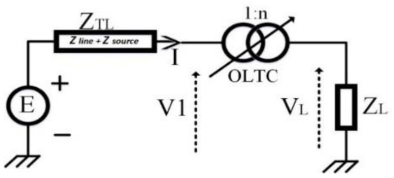

Figure 1. A simple power system with an OLTC transformer

From the system seen in Figure 1.

$$E = Z_{TL} I_{TL} + V_1 \tag{1}$$

and

$$I_{TL} = \frac{E}{Z_{TL} + {}^{Z_L}/_{n^2}} \tag{2}$$

From (1) and (2)

$$V_1 = E - \frac{Z_{TE}}{Z_T + {}^{Z_L}/_{n^2}} = E - \frac{E\, Z_T\, n^2}{n^2\, Z_{TL} + Z_L} \tag{3}$$

$$V_L = n\, V_1 \tag{4}$$

From compensating (3) in (4).

$$V_L = n\,E - \frac{E\,Z_{TL}\,n^3}{n^2 Z_{TL} + Z_L} \tag{5}$$

The rate of change of V_L as the n of the OLTC was: $\frac{\partial V_L}{\partial n}$ which leads as (6).

$$\frac{\partial V_L}{\partial n} = \frac{E\,Z_L^2 - n^2\,E\,Z_{TL} Z_L}{(n^2\,Z_{TL} + Z_L)^2} \tag{6}$$

Here, if $\frac{\partial V_L}{\partial n}$ is positive, the system will be able to return to stability after the voltage drop. Therefore, the system will be dynamically stable. However, if $\frac{\partial V_L}{\partial n}$ is negative, the system will remain unstable after the voltage drop as the rate of change is less than zero. Here as (7):

$$\frac{E\,Z_L^2 - n^2\,E\,Z_{TL} Z_L}{(n^2\,Z_{TL} + Z_L)^{20}} > 0 \tag{7}$$

Dividing on $(Z_L\,E)$. Therefore, the n of a stable system will be as (8):

$$n\ <\ (\frac{Z_L}{Z_{TL}})^{0.5} \tag{8}$$

And the n of an unstable system will be as (9):

$$n > (\frac{Z_L}{Z_{TL}})^{0.5} \tag{9}$$

The turn ratio of the transformer changed if the load changed, the source voltage (Vs) changed, or if both occurred. Three different cases were simulated in MATLAB for different values of source voltage with increasing load and are discussed in the next section.

2.2. Explanation of OLTC reverse action

The reverse action of the OLTC is when the OLTC acts inversely on the system voltage. Where the OLTC secondary voltage decreases as the turn ratio increases [23]. A chain of events can be used to explain the reverse action phenomenon as given in the following sub-paragraphs.

2.2.1. Mathematical explanation

The reverse action of a simple system can be mathematically explained easily using the following correlation: $Z_L\ < n^2\ Z_{TL}$. A collapse occurs when the system load increases, the load impedance decreases, and the voltage decreases causing the OLTC to increase the voltage by increasing the turn ratio (n). This causes the value on the right-side of the equation to increase and the value on the left-side to decrease. The OLTC will then once again attempt to increase the voltage by increasing (n). This, however, only causes the value on the right-side of the equation to increase further. A collapse becomes inevitable, as the OLTC will repeatedly attempt to restore the voltage to its base value. It is noteworthy that the correlation between $Z_L\ , n^2, and\ Z_{TL}$ only apply to small systems [26].

2.2.2. System reactive power explanation

When the system load increases by large values, the current of the load increases to meet the load demand. This increases the system loss and the reactive power, thereby decreasing the active power and load voltage [27]. The OLTC will then try to restore the voltage to its base value by increasing (n) by adding more turns to the windings. These extra windings add more reactance, which in turn, adds more reactive power to the system, resulting in more and more voltage drops. Therefore, the addition of more windings increases the voltage drops.

2.3. Methods of improving the OLTC performances in power systems

The voltage stability and the OLTC performances in a power system can be improved by four main methods:

- Increasing the step voltage: increasing the step voltage of an OLTC transformer enables it to restore the base voltage after a disturbance occurs, especially if the load increases exponentially over a short period of time. But, that increase will raise the OLTC cost [28].
- Expanding the bandwidth: the number of steps of an OLTC are called bandwidth. The bandwidth of an OLTC affects the amount of power at the collapse point as more tap windings equate to more voltage compensation. Therefore, a higher number of taps will help an OLTC achieve the desired voltage value [14].
- Decreasing the delay time: delay time is a specific period of time that must elapse before the OLTC controller decides to change the tap position. This helps prevent the OLTC from responding to transient disturbances such as motor starting. However, if the delay time is too long, it will prevent the tap from matching the voltage drop when the load is heavy and continuous [29].
- Decreasing the switching time: switching time is the duration that tap switches require to change their positions. It is important to reduce switching time as much as possible to improve OLTC performance [30]. Therefore, many recent studies [20], [31]–[35] have offered new control and switching techniques for reducing the switching time.

This present study conducted a set of individual checks in MATLAB by adjusting the parameters of the proposed methods to examine their efficacy. Two cases of disturbances; an increase in load and variation in voltage source (V_s), were used to test system response. Four methods of improving voltage stability with an OLTC also examined.

3. MODELLING RESULTS AND DISCUSSION

3.1. Proving the effective of (8) and (9)

This section discusses the three models that were simulated in MATLAB to prove that the obtained equation was effective for voltages above or below the ideal value. The first case at source voltage 1 p.u. The second case at voltage source 0.90 p.u. And the third case at voltage source 1.10 p.u.

3.1.1. First case: $V_s = 1\ p.u.$ with increasing load

The results were obtained using MATLAB/Simulink. The abovementioned equations were then used to determine the n and verify its effect. A comparison between the values of n from the two methods will be done.

a. Determining the collapse point in MATLAB/Simulink for $V_s = 1\ p.u.$

The simulation results of a system in Figure 2 can be seen in Figure 3 with a variable increasing load and a voltage reference of OLTC$= 1\ p.u$ with $Z_{TL} = 1.5 + j1.34\ \Omega$. As seen, when the load increased gradually on the secondary side of the OLTC, the collapse occurred when the critical load power reach $67.9 + j56.6$ MVA. Therefore, $Z_L = 2.365 + j2.126\ \Omega$ at n = 1.26. The system approached collapse at these values. The P-V curve shown in Figure 3 depicts the stable area of the system.

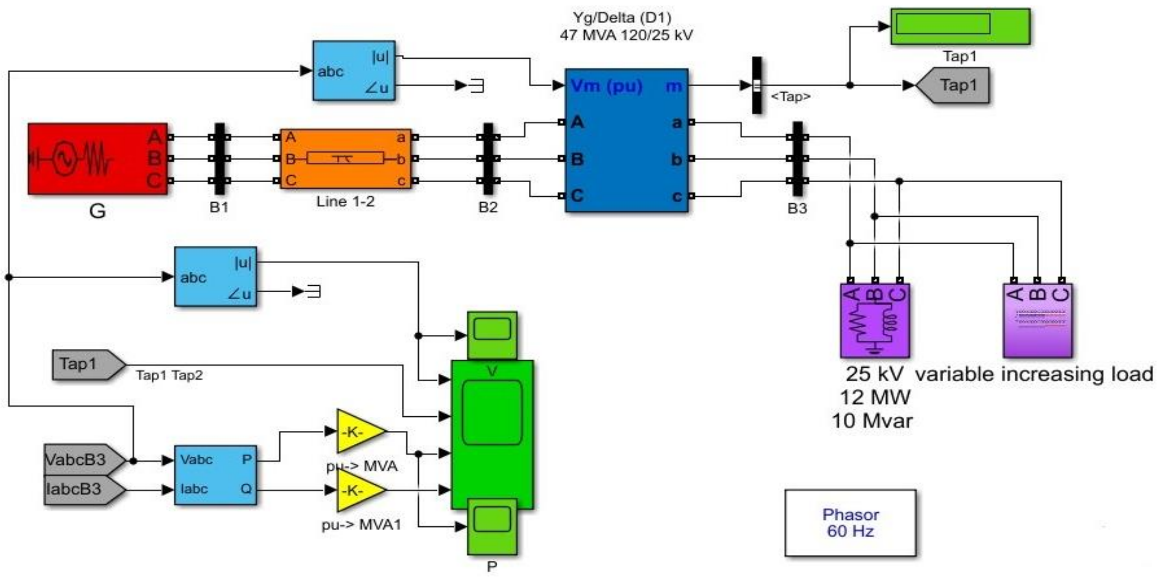

Figure 2. The system modelled in MATLAB

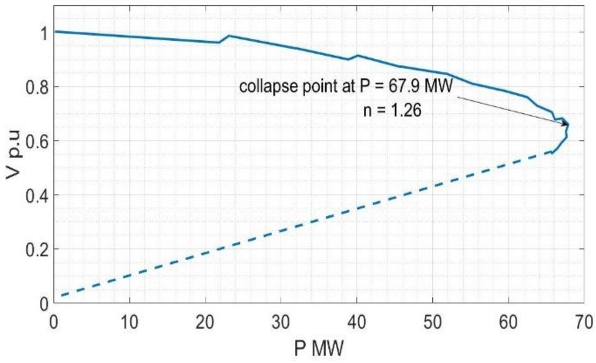

Figure 3. The P-V curve of $V_s = 1\ p.u$

b. Determining the n of a stable system at $V_s = 1\ p.u.$ to mathematically prove (8) and (9)

As the system seen in Figure 1 has an impedance of $Z_{TL} = 1.5 + \mathrm{j}1.3\Omega$ and $Z_L = 2.365 + \mathrm{j}1.972\Omega$, according to (8) and (9), the n needs to be < 1.26 for the system to be stable. That value is the same as the value that was found by the Simulink. The result proves the validity of the used equations.

3.1.2. Second case: $V_s = 0.90\ p.u$ with increasing load

In this case, the source voltage (V_s) will decrease. The V_s drops causing the n to change. Which in turn affects the power output. Nevertheless, (8) and (9) remained effective.

a. Determining the collapse point in MATLAB/Simulink for $V_s = 0.90\ p.u.$

The system depicted in Figure 2 was reused, but with $V_s = 0.90\ p.u.$ The OLTC tried to compensate for the drop in the primary side of the voltage by increasing the n to 1.29. However, the drop in voltage had reduced the transfer power, thereby causing the OLTC to load throw to $55.6 + j46.35$MVA. Therefore, the load impedance was $Z_L = 2.348 + j1.957\Omega$ and the collapse began at the point shown in Figure 4.

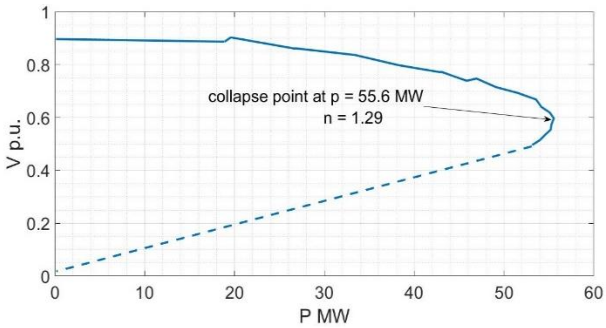

Figure 4. The P-V curve of $V_s = 0.90\ p.u$

b. Determining the n of a stable system at $V_s = 0.90\ p.u.$ to mathematically prove (8) and (9)

In MATLAB/Simulink, the load power of the collapse point was $55.6 + 46.35$ MVA and $Z_L = 2.348 + 1.957\ \Omega$ with the same transmission line of $Z_{TL} = 1.5 + \mathrm{j}1.3\ \Omega$. According to (8) and (9), the collapse would occur when $n > 1.29$. The value of (n) is the same as that found in the simulation too.

3.1.3. Third case: $V_s = 1.10\ p.u$ with increasing load

In this case, the source voltage (V_s) has increased to 1.10 p.u. The V_s increases causing the n to change which, in turn, affects the power output. Nevertheless, (8) and (9) remained effective.

a. Determining the collapse point in MATLAB/Simulink for $V_s = 1.10\ p.u.$

The system depicted in Figure 2 was reused, but with $V_s = 1.10\ p.u.$ The OLTC tried to increase the secondary voltage by decreasing the n to 1.23. However, increasing the V_s caused a power increase. Therefore, the load power at the collapse point was $80.9 + j67.4$ MVA. Figure 5 shows the collapse point and the maximum power.

b. Determining the n of a stable system at $V_s = 1.10\ p.u.$ to mathematically prove (8) and (9)

In MATLAB/Simulink, the load power of the collapse point was $80.9 + \text{j}67.4$ MVA and $Z_L = 2.202 + 1.835\ \Omega$, with the same transmission line of $Z_{TL} = 1.5 + \text{j}1.3\Omega$. According to (8) and (9), the collapse would occur when $n > 1.23$. Therefore, the system may be able to re-stabilise if the n is below this value.

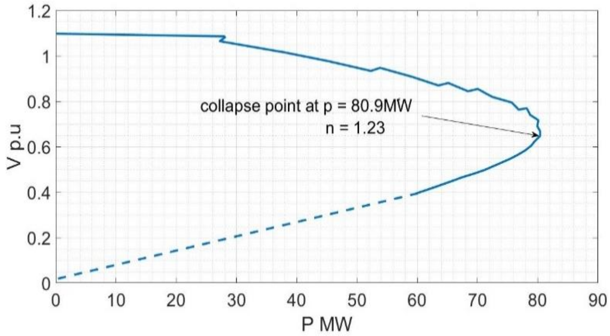

Figure 5. The P-V curve of $V_s = 1.10\ p.u$

3.2. Proving the affectivity of OLTC improving performances methods

The OLTC performances depend on its rating values. Changing some of those values could increase the OLTC performances. This present study tested a few methods to determine their ability to improve the performance of OLTCs in power systems.

3.2.1. Increase OLTC step voltage

In the case of the system seen in Figure 2, the load was heavy and increased in a large step. Therefore, if the step voltage was low (1%), the collapse would have occurred faster than if the step voltage was high (1.875%). When the step voltage was low and high, the collapse points were $P_L = 64.8\ MW$ and at $P_L = 67.9\ MW$, respectively. The simulation results provided in Figure 6 explains the difference.

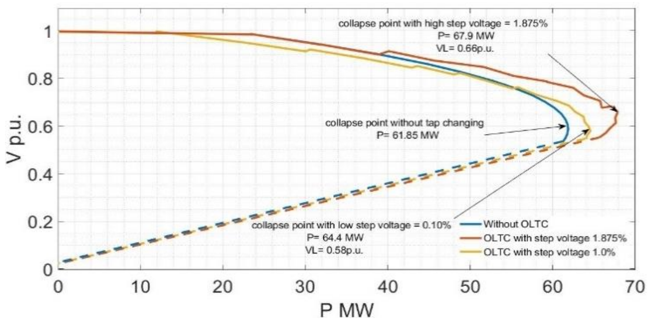

Figure 6. The P-V curve of different step voltages

Therefore, step voltages should be taken into consideration during OLTC selection with respect to the type of load. The OLTC cost should be considered. Because the extra winding which performs the higher step voltage, will add more costs to the OLTC manufacturing.

3.2.2. Reduce OLTC delay time

To view this method effect, Figure 7 compares the OLTC performance of the Figure 2 system with long (15 s) and short (10 s) delay times. The collapse points of the long and short delay times were $P_L = 66.4\ MW$ and $P_L = 67.9\ MW$, respectively. Reducing the delay time of the OLTC will increase the working area under the P-V curve.

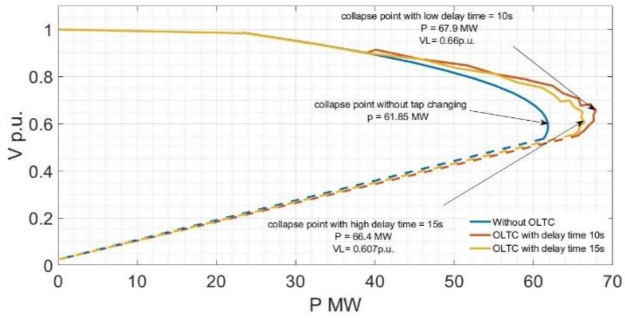

Figure 7. The P-V curve of different delay times

3.2.3. Reduce OLTC switching time

Figure 8 compares the OLTC performance of the Figure 2 system with long (10s) and short (5s) switching times. The collapse points of the long and short switching times were $P_L = 66.45\ MW$ and $P_L = 67.9\ MW$, respectively. The effect of decreasing the switching time can be noticed obviously on the P-V curve.

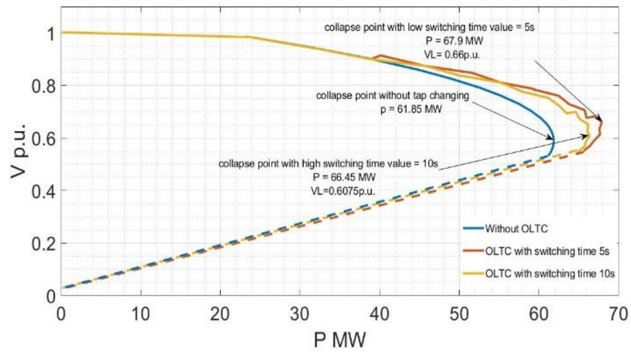

Figure 8. The P-V curve of different switching times

3.2.4. Increase OLTC voltage steps

Figure 9 clearly illustrates the effect of bandwidth. Two-different cases were modeled for 33 step and 15 step. The maximum power limits on the P-V curve will clearly show the benefits of increasing the number of steps. At 15 steps, $P_L = 65.2\ MW$ while at 33 step it was $P_L = 67.9\ MW$.

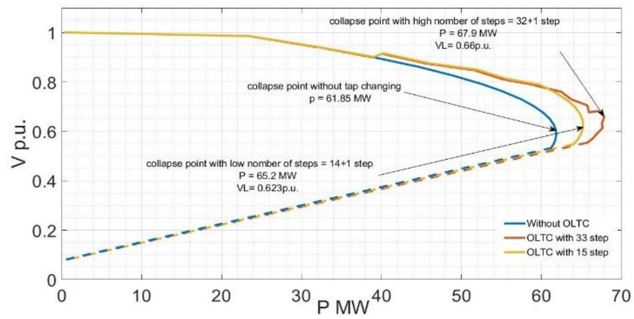

Figure 9. The P-V curve of different bandwidths

4. CONCLUSION

An OLTC transformer is a device that is used to stabilize the voltage. It helps most systems remain within the voltage stability band when disturbances occur and increase the value of the power at the collapse point. In this paper, the results show that the collapse point for the used radial power system when the load increased without OLTC was at P=61.85 MW. While with the OLTC it was at P=67.9 MW.

However, its reverse action phenomenon is sometimes responsible for a collapse. Nevertheless, some methods can be used to prevent a collapse or to increase the power at the collapse point in the hopes of restoring the voltage to a stable margin. The findings of this present study indicate that some OLTC parameters, such as step voltage, delay time, bandwidth, and switching time, should be chosen according to the type of load to reap the most benefits of using an OLTC transformer. In this paper, the results also show that increasing the step voltage improves the value of power from 64.4 MW to 67.9 MW. Like that, increasing the number of steps improves the power value from 65.2 MW to 67.9 MW. When the delay time was minimized, the power value improved from 66.4 MW to 67.9 MW. As well, decreasing the switching time resulted in power increasing at the collapse point from 66.45 MW to 67.9 MW.

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