Design and Simulation of Improved On Load Tap Changer (OLTC) to Mitigate Voltage Sag/Swell

ADNAN AHMED NOOR ULLAH MUHAMMAD IDREES
Department of Electrical Engineering
COMSATS institute of Information Technology, Islamabad
Park Road, Chak Shehzad, Islamabad, Pakistan
adnan.khan13566@gmail.com, engr.noorullah@gmail.com, engr.idrees85@gmail.com,

Abstract: - Many electrical and electronics equipments miss operate or stop working during voltage sag and swell. Due to this the entire industrial process disturbs, which leads not only to great financial loss but also caused of many accidents. Therefore it is necessary to avoid the tripping of these equipments during voltage instability or voltage sag /swell. There are some typical FACT devices which are used for voltage regulation i.e. DVR, STATCOM, UPFC and back to back converter. However these devices are not only costly but the synchronization of the voltage is also a challenging task. In this research work the conventional OLTC is replaced with a new one OLTC having the ability of fast transfer switching to mitigate voltage variation very fast. The fast transfer switching is made possible via bi-directional power triacs. The OLTC is connected to three phase variable power supply, the variable power supply is varied from 150 to 250 Vrms and the output voltage is measured by voltmeter and found in the range of 210 - 230Vrms which is a nominal voltage of a 220 Vrms system. The OLTC tap switching time is analyzed by oscilloscope and the results are shown below.

Key-Words: - Power Quality, Voltage Sag/Swell, DVR, OLTC, Fast transfer switch

1. Introduction

The electrical and electronics equipments sensitivity depends on RMS voltage magnitude and duration. When a voltage sag or swell occurs in electric power system some electrical equipments operate in normal condition, some equipments miss-operate or mall functioning or damage and some equipments do not operate. Voltage sag is the reduction in RMS voltage for short duration (from half cycle to 1 minute) caused by fault on power system or starting of large loads like heavy motors in industry. A voltage swell is an increase in RMS voltage level for short duration (half cycle to 1 minute) caused by switching on/off of capacitor bank, lightning and sudden tripping of heavy loads. Typically RMS voltage sag magnitude is 0.9 to 0.1 pu and RMS swell magnitude is from 1.1 to 1.8 pu. Nowadays customers use a lot of digital and information technology equipments and these equipments are very sensitive to voltage sag and swell. Microprocessor based equipments are operated at very high speed and making very fast decisions in micro and milliseconds and can be very easily effected by voltage sag and swell. [1-3]

2. Problem Statement

Voltage sag, swell and interruption normally occur due to faults on power system i.e. lightning, winds, line to ground faults, animal contact, week insulation and faults in distribution system like fault on parallel feeder. Starting of heavy load (induction motor), switching ON/OFF of a transformer or capacitor bank also produce voltage sag and swell. Symmetrical faults are 3 phases Line to line (3LL) and 3 phases phase to ground (3LG). Such faults are balance in sense that system remains symmetrical. In symmetrical faults short circuit current remains the same in all phases [4-5]. KVA capacity at faults point is

$$KVA_{SCC} = \sqrt{3}\, V_{LL}\, I_F \quad (1)$$

$I_F = \frac{V_{LG}}{Z_F}$ (A), $I_F = \frac{V_{LG}}{X_F}$ The value of R is very small so is neglected.

Unsymmetrical faults involves single or double phases, in such faults all the line become unbalance Voltages in all phases become unbalance and also current is different in all phases [4-5].

Phase Angle shift

$$\Delta\Phi = \tan^{-1}\left(\frac{X_F}{R_F} - \frac{X_S + X_S}{R_S + R_F}\right) \qquad (2)$$

and $Z_s = R_S + jX_S$, and $Z_F = R_F + jX_F$

Large size induction motor draws excessive current which is five to ten times more than the normal current and decreases as motor speed reaches to rated speed [6-8**].** The starting heavy motor causes voltage sag which is given by

$$V_{Sag} = \frac{V.kVA_1}{kVA_2 + kVA_1} * 100\% \qquad (3)$$

where V= system voltage, kVA_1 = Short-circuit kVA, kVA_2 =motor locked rotor kVA

$$kVA_{LR} = \sqrt{3}V_{LL}I_{LR} \qquad (4)$$

Induction motor starting current

$$I_S = \frac{V_1}{\sqrt{(R_1 + \frac{R_2}{S})^2 + (X_1 + X_2)^2}} \quad Amp \qquad (5)$$

Value of slip is between 0 and 1, Lock rotor current is in Amp, where the value of slip S=0

Transformer draws more current when switch on that current is called inrush current due to excitation and magnetization of iron core and coil. Iron core does not energize quickly when the voltage magnitude goes to zero. The inrush current will take 5 to 6 cycle to go to normal value and during this time voltage sag is generated. The energy required to neutralize the residual flux is called hysteresis loss. The inrush current miss operates the differential relay, caused DC offset and generates different harmonics. [9].

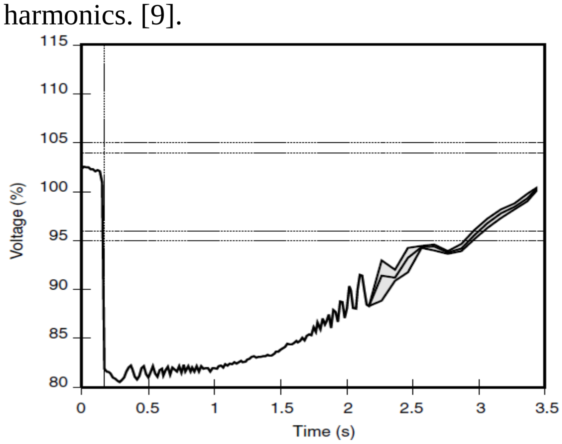

Figure.1 Voltage sag due to starting of induction motor

$$V_{sag} = V_L \frac{X_T}{X_T + X_S} \quad (pu) \qquad (6)$$

X_T = Transformer short circuit reactance, X_S = Source equivalent reactance

Static capacitor with large motor also produces voltage sag for few cycles of AC frequency. With one or more stages previously capacitor bank energized, the transient peak inrush current to the bank may exceed 200 times the normal peak steady state capacitor current. For the common case of switching two steps of equal sized kVAr, this is referred to as "back-to-back" switching. The maximum peak value of inrush current is calculated from the equation (7).

$$I_P = kV_L \sqrt{\frac{kVAR}{L}} \quad (Amp) \qquad (7)$$

kV_L = Line to Line voltage in kV, $kVAr$ = Capacitor ratting, L= Series inductance in micro henrys [2]

Effect of Voltage sag and Swell: Personal computers and information technology (IT) equipments are very sensitive to voltage sag and swell, and can be also affected. In 1983 a standard was proposed for personal computers voltage acceptability curve named CBEMA. The voltage acceptability curve CBEMA was revised and remand ITI curve, in 1995.Another curve similar to ITI curve for semiconductor processing equipment known as SEMI F47 was proposed currently. It specifies voltage acceptability with duration from 50 m sec up to 1sec.[10-12] Electromagnetic relays and contactors, fluorescent lamps and high intensity discharge lamps, PLC and PIDs equipments and adjustable speed drives (ASDs) are the most common sensitive equipments to voltage sag, swell and interruption. [13-15].

3. Hardware of 3 phase OLTC

3.1 Working principles of power transformer:

A power transformer is a static machine used to transform power from one circuit to another without changing frequency via increasing or decreasing voltage. Since there is no rotating or moving parts that why transformer is known as static machine. Transformer operates on AC power supply and its working principle is based on the mutual induction. It is used in generation, transmission and distribution substations for power transforming, voltage regulation and phase shifting. The ratting capacity of power transformer can be expressed in KVA or MVA. The voltage of the transformer is controlled with changing the positions of different winding tap. The tap changer in power transformer is a huge and complex electromechanical system and operates very slowly. It takes 3-10 seconds duration to change the position of one winging tap to another. When a voltage sag or dip occurs, some equipments are so sensitive and trip within a few cycles of sinusoidal voltage. In this research work, power transformer is used as a voltage control device, to regulate line voltage and to eliminate voltage sag and swell. Power triacs are used for switching purposes of the winding taps and the switching time of these triacs is about 10 milliseconds. Some mathematical work is carried out to understand the operation of a power transformer.

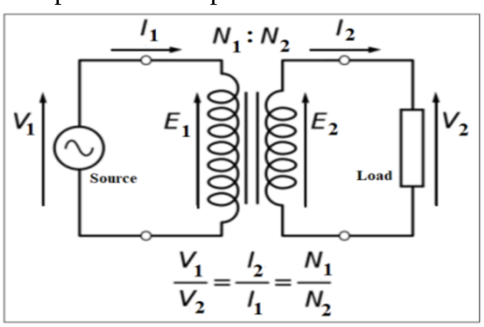

Figure (2) Transformer circuit

In the power transformer:

$$\frac{N_1}{N_2} = \frac{V_1}{V_2} \quad (8)$$

Input or primary voltage: $V_1 = V_2\left(\frac{N_1}{N_2}\right)$ (9)

Output or secondary voltage $V_2 = V_1\left(\frac{N_2}{N_1}\right)$ (10)

Transformation Ratio

$$k = \frac{N_1}{N_2} = \frac{V_1}{V_2} = \frac{I_2}{I_1} \quad (11)$$

Flux Density $\Phi_M = B_M \times A$ (12)

Primary Induced voltage $E_1 = 4.44 f \Phi_M N_1$ (13)

Secondary Induced voltage $E_2 = 4.44 f \Phi_M N_2$ (14)

Efficiency

$$= \frac{\text{output power}}{\text{input power}} = \frac{\text{input power - losses}}{\text{input power}} \quad (15)$$

$$\eta = \left(1 - \frac{\text{losses}}{\text{input power}}\right) \text{ x } 100\% \quad (16)$$

[16-17]

3.2 Hardware designing

In figure 3 the circuit diagram of three phases OLTC is shown. Five different winding taps with different switches are connected to each phase of the primary winding. When the input voltage decreases the output voltage also decreases, to maintain voltage level at secondary side of the transformer decrease the primary winding turns via different taps. In this project five taps per phase is used for OLTC to control voltage from 150VAC to 250VAC, and the level of the output voltage will be 210VAC-230VAC.

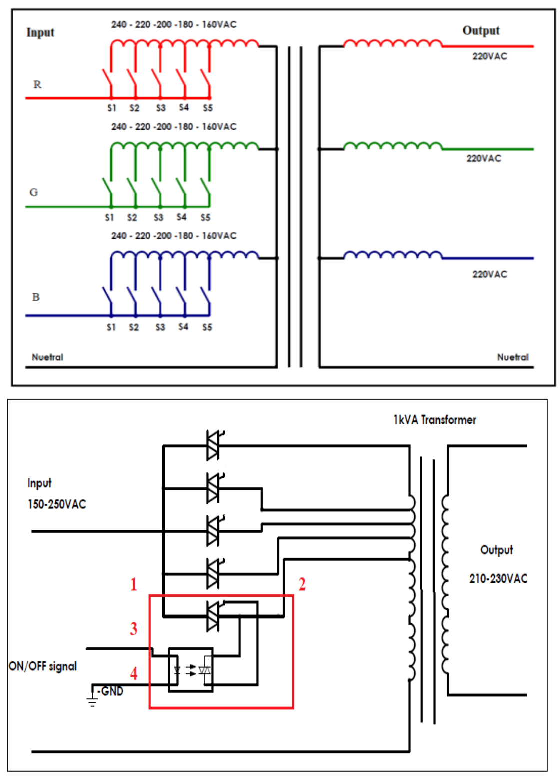

Figure 3. Circuit diagram of three phase power transformer with on load tap changer

3.3 Measuring and Control Circuit: Three phases voltage is also given to measuring transformers or potential transformers (PT), which step down the primary voltage from 220 VAC into 6 VAC. Rectifier bridges convert the AC voltage into pulsating DC, capacitors are used for filtering and smoothing these voltage signals. A 10 kΩ variable resistor is used to adjust and calibrate the measuring voltage. The output of the measuring voltage circuits are adjusted at 2.5VDC which are provided to Arduino microcontroller in analogue read pins. Thus micro controller read the input 2.5VDC signal which represents the 220VAC. When the 220VAC in the input circuit of OLTC transformer increases then the measuring signal of 2.5VDC also increases and vice versa. In the Arduinno programming software the analogue read signals can be calibrated and display in the serial monitor window. After calibration the input voltage is compared to some pre defined values, micro controller generates a high signal to switch on the appropriate power triacs.

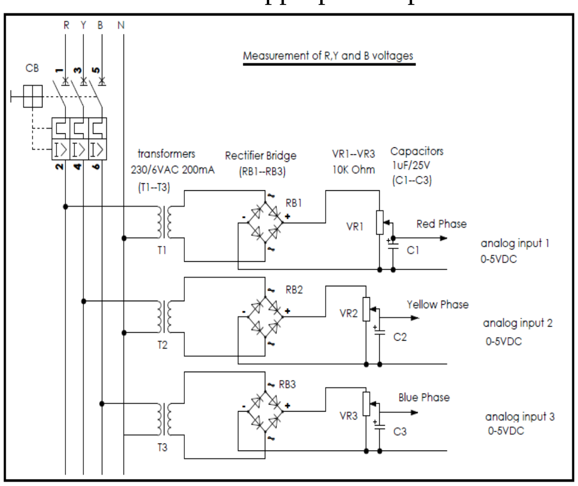

Figure (4a). Three phase voltage measurement circuit for OLTC, Interfacing of opto triacs MOC 2023 with power triacs and micro controller

3.4 Operation of OLTC circuit: When the input voltage of OLTC is between 210 and 230 VAC, the switch (triac) S2 will closed, all the rest of switches will remain open and the output voltage will also between 210 and 230 VAC.

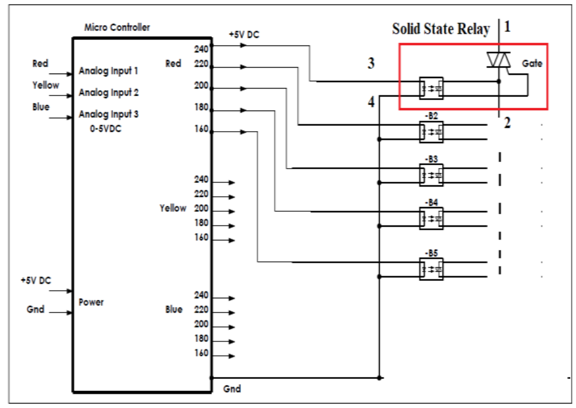

Figure 4. Three phase voltage measurement circuit for OLTC, Interfacing of opto triacs MOC 2023 with power triacs and micro controller

No switch will change its state when voltage varies between the 210 and 230 VAC. When the input voltage rises up from 230 to 250VAC, the switch (triac) S1 will closed, all the rest of switches will remain open and the output voltage will also between 210 and 230 VAC. Similarly when a voltage sag or dip occurs or voltage drops below 210 to 190 VAC, the switch (triac) S3 will closed, all the rest of switches will remain open and the output voltage will step up between 210 and 230 VAC. The operation of the OLTC is so fast and quickly to mitigate voltage sag and swell. In the power transformer the operation of OLTC is very slow to mitigate voltage sag and swell, most of sensitive electrical and electronics equipments fail during voltage and swell. The operation of relay based OLTC takes more than 100 milliseconds to change the position of winding tap. But the voltage at output of the transformer is remaining disturbed for 100 milliseconds. In this research work the operation of OLTC is designed on power triacs which change the position of winding taps so fast and quickly, the voltage at output of the OLTC remained stable. The three phase voltage signals are provide to the analogue read pins (0-5 VDC) of the Arduino microcontroller. An analogue to digital converter (ADC) built-in in Arduino board converts the analogue voltage signal into digital from 0-1023 decimal values. Voltage signals are connected to these pins A0:V1, A1:V2, A2:V3

3.5 Simulation of OLTC in MATLAB/Simulink:

The simulation blocks consist of voltage source, voltage and current measurement, and RL load and OLTC blocks. The designed OLTC has three single phase transformers; each transformer consists of different tap winding position. The bi-directional switches (Triacs) are used to connect the transformer taps to the power supply.

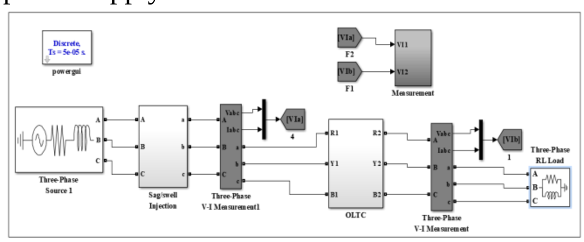

Figure: (5) Modeling and Simulation of OLTC in MATLAB/Simulink

A fault is injected in the transmission line in order to generate voltage sag. The magnitude of voltage sag depends on type of fault, fault impedance, number of parallel transmission line and distance between fault and point of common coupling.

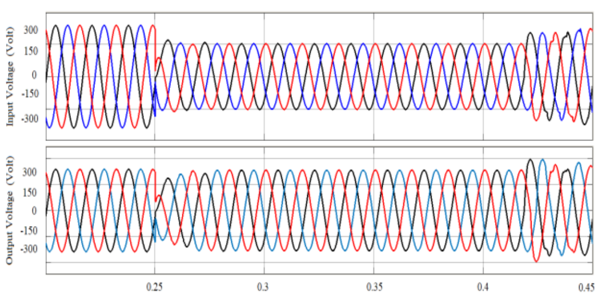

Figure 6. Voltage sag generation and restoring, the voltage is restored in about 5 milliseconds

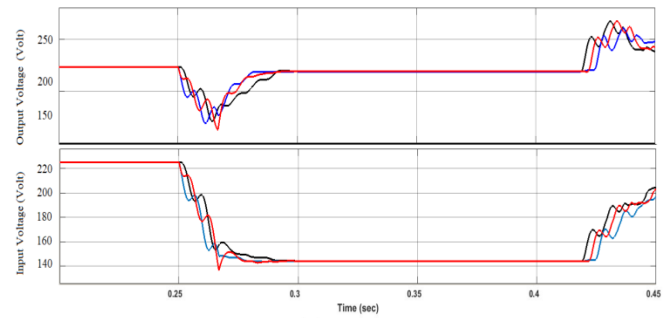

Figure 7. Voltage sag generation and restoring, RMS Voltages

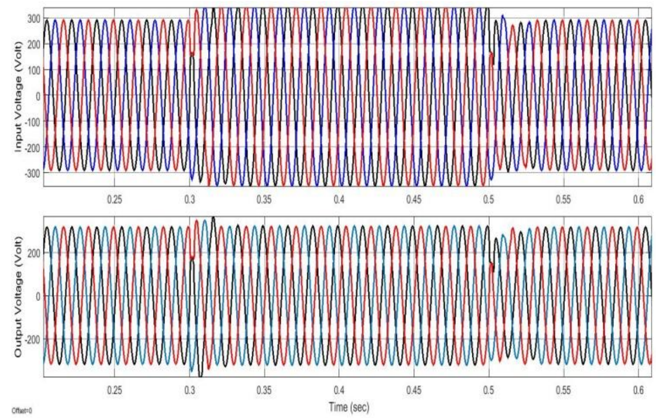

Figure 8. Voltage swell generation and restoring

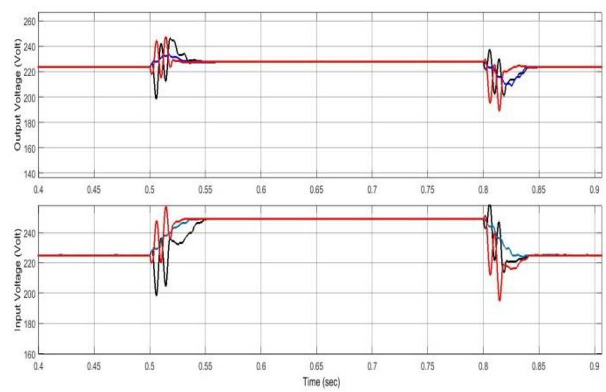

Figure 9. Voltage swell generation and restoring, RMS Voltages

The following results are taken from electromechanical tap changer .When a sag occur on the system it is the restored more than 30 sec black highlighted line shows this duration

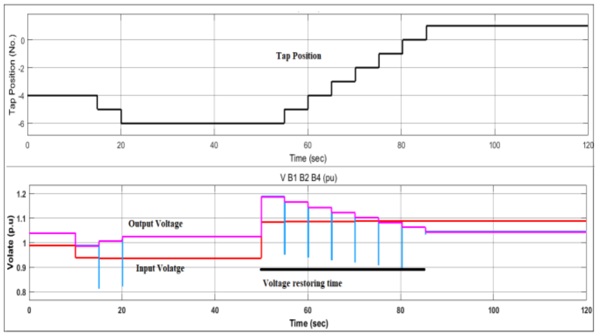

Figure10. Voltage restore by Electromechanical Tap Changer

Two volt meters are connected in the input and output of the OLTC, The OLTC is then connected to three phase variable voltage AC supply source. The variable voltage supply is varied from 220VAC to 150VC, at 151.4 VAC input AC the output voltage was 209.2. Similarly the voltage varied from 150AC to 250VAC the output voltage was measured and shown on volt meters. The results are shown in Table 1 and figur

Table 1 Input/output Voltages and currents of OLTC

Tap Position	V_1 (V)	I_1 (Amp)	V_2 (V)	I_2 (Amp)
1	240 V	5.1 A	220 V	4.55 A
2	220 V	5.5 A	220 V	4.55 A
3	200 V	6.0 A	220 V	4.55 A
4	180 V	6.5 A	220 V	4.55 A
5	160 V	7.3 A	220 V	4.55 A

4.1 OLTC and D-UPFC in IEEE 9-Bus system for voltage stability

In this simulation work, the IEEE 9-bus system with DUPFC and OLTC has been presented and modeled in MATLAB Simulink software. Voltage sag and swell is generated and restored by using FACTS controllers and OLTC. IEEE bus systems are used by researchers to implement new ideas and concepts.

This WSCC 3 Machines, 9 Bus Test Case (known as P.M Anderson 9 Bus) represents a simple approximation of the Western System Coordinating Council (WSCC) to an equivalent system with nine buses and three generators. [23][26]

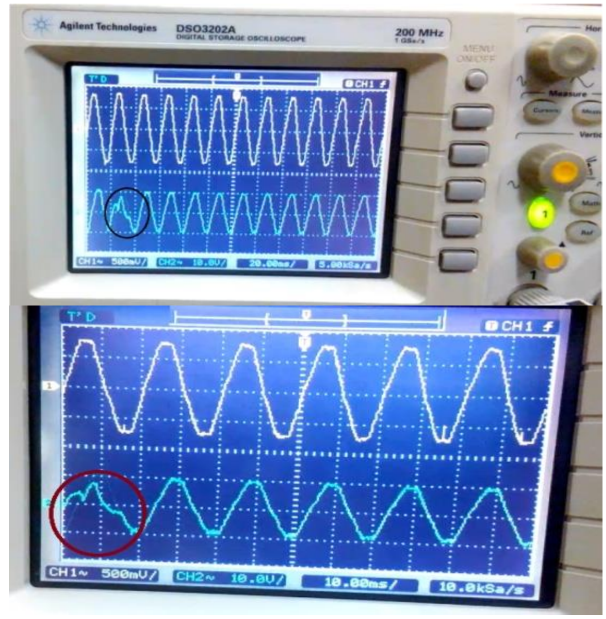

Figure 11. Switching time of OLTC (hardware) is measured by using Oscilloscope

In this simulation the test case consists of nine numbers of buses, three numbers of generators, 3 numbers of two-winding power transformers, 6 numbers of lines and 3 numbers of loads. The detailed circuit diagram of the 9-bus test system is shown in Figure. Disturbances in the amplitude or wave shape of voltage and current in electric system is common now a days these type of conditions could cause failure in the equipment's and raise the possibility of an energy interruption .The voltage variation that mainly appears in duration of 10 sec or less are called voltage sag and swell .These variations are produced during normal operations by the connection and disconnection of high power loads. Maximum disturbances are produced by voltage sag. Different techniques are used to compensate these voltage variation problems. D-UPFC is used in a radial network in order to control voltage sag and swell. It the back of the transformer pole a D-UPFC is installed and connected to load side, which continuously reshape the output voltage to be sinusoidal. Using matrix arrangement ac to ac converter generates power and a series transformer compensates the voltage to the load. Use UPFC & IPFC interline power flow controller which is used to control the power flow in the multiple line system .The basic purpose of IPFC is to compensate the real power in the transmission line system[18]. Use OLTC with control scheme LDC Line drop compensation. LDC monitor the voltage level at the secondary side of transformer and then current is measured at the secondary to mitigate the voltage drop across the feeder between load and transformer .This voltage of feeder impedance is used to rise the voltage at the transformer terminals therefore to obtain the actual voltage level sustains at the load side where it is require. AVC automated voltage control based OLTC provides an automated tap changer control without communication unit it also include the SDC scheme source drop compensation. SDC finds the voltage at the point of regulation by the source current and the impedance of the feeder between up and down stream [19] OLTC is combined with the distribution system using voltage rang as an input parameter between the substation and the first node the strings voltage drop or rise is taken into account which enables the similar loading consideration in the strings of distribution grids [20]. Aim of this research work is to compare the performance of UPFC and OLTC voltage compensation at the distribution side of nine bus radial network. D-UPFC is best to use on load side bus to control voltage level and VAR compensation but not too good to use on distribution side beside this it has some disadvantages like it has very complicated structure of inverter converters are used and voltage injection synchronization is also a tough job and it produce a lot of harmonics in a system. On the other hand bidirectional solid state switches based OLTC is best to use on distribution side its structure is very simple and easy to handle OLTC has no control option for VAR compensation but we can installed VAR compensation banks to each load on distribution and it is not a big deal. Full electronic based OLTC which has same performance to ordinary electro mechanical OLTC which use step wise regulation of voltage with high number of switching fast operations. Each tap is connected to supply voltage through bidirectional solid state switches. The corresponding tap is selected by switching on the bidirectional solid state switch while all other switches at that time will be OFF. Current is commutating from one switch to the next position by changing the tap position. [20][22][25]

UPFC: The power systems are complex, huge and extensive. Due to increasing the demand of power the transmission lines are becoming overloaded. As the heavy load on the transmission line increases the voltage stability of the power system is worst affected. The other parameters of power system which are affected are the rotor speed, current, power flow and other system variables. Voltage stability is an important aspect in designing of a power system. Power system stability is the ability of the system, for a given starting condition, to retain a normal state of equilibrium after being subjected to any fault. To improve the voltage stability of the power system, FACTS devices are used rather than installing new transmission lines. UPFC is used to control voltage and compensate reactive power. UPFC has shunt transformer, converter, capacitor bank, inverter and series transformer. The inverter is used to convert dc voltage into ac voltage, the ac voltage is then injected into power transmission lines through series transformer. The injected voltage has same phase sequence and phase angle as that of the transmission line. However when voltage swell occurs the inverter voltage is injected in opposite phase sequence. The magnitude of injected voltage depends on voltage sag or swell occurs in transmission line. The phase angle of the injected voltage can be set for the compensation of the reactive power. D-UPFC is actually UPFC used in distribution networks. [19][24][26]

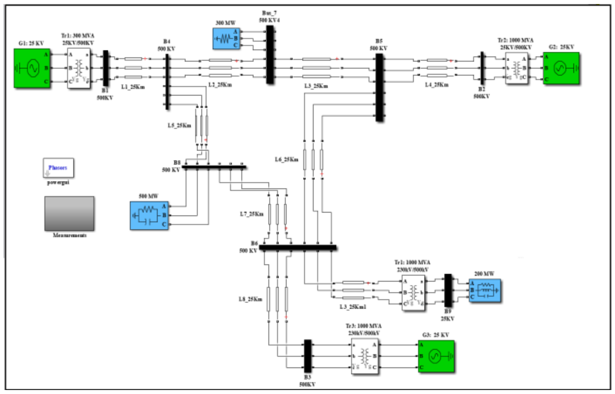

Figure 12 IEEE 9-Bus System and the main components

4.2 Generation of voltage sag swell or voltage instability in IEEE 9-Bus system

A three phase fault has been applied on bus 8 and the overall effect can be seen in figure 14 and 15, all buses from bus 1 to bus 9 experienced voltage sag or dip for duration of 4 seconds. Bus 8 experienced a high voltage dip because it is near to the fault and bus 1 experienced the least due to far from the fault. A swell has been generated by connecting of a high power capacitor bank. The capacitor bank is connected to bus bar system via a circuit breaker which operates in 0.3 seconds. The overall effect on 9 bus system is shown in figure 14, in which bus5 has experienced more voltage swell then all other buses because it is near to the fault location. The voltage magnitude is measured on bus 6 and compare with a constant value 0.95 if the voltage is less than 0.95 pu, the UPFC will be connected through the circuit breaker to restore the line voltage.

Three phase OLTC is also connected in 9-bus system at bus number 9 and a three phase fault is added on bus 6 in fig. The results in both sag and swell condition can be seen in figure 17, which clearly examine that voltage is restored in just mille second of duration.

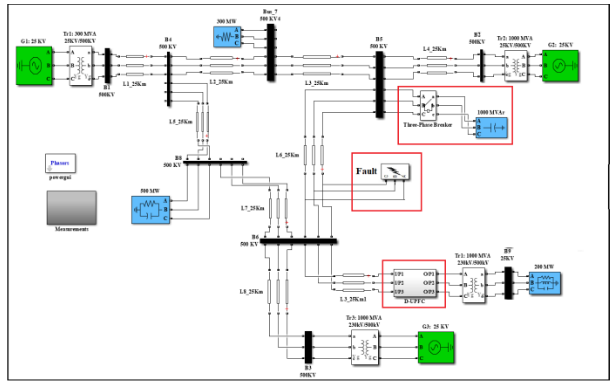

Figure .13 UFPC is used in 9-Bus system to stabilize the voltage during voltage instability

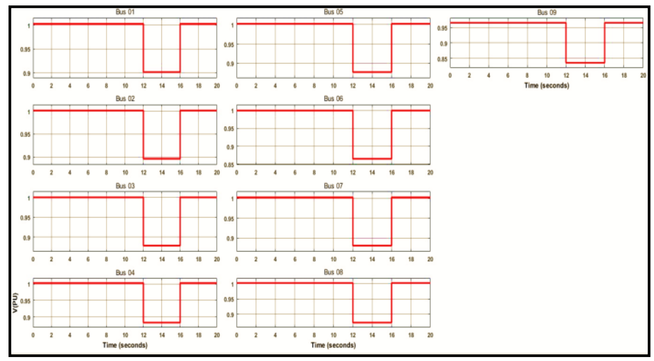

Figure 14. IEEE 9-Bus System Voltage Profile during Sag

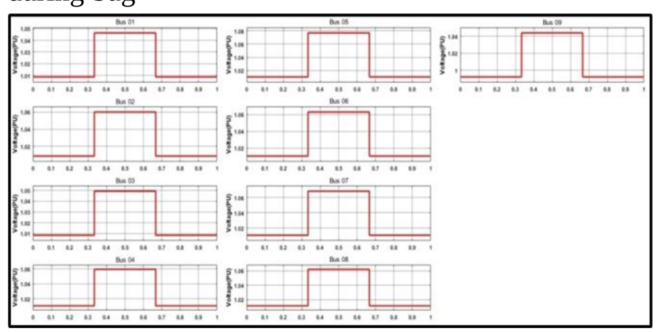

Figure 14. IEEE 9-Bus System Voltage Profile during Swell

The system performance is badly affected by three phase fault .To enhance the system performance a D-UPFC is connected on bus 9 as shown in fig: on distribution side to a 200MW load .When fault occur on all buses that causes sag only on bus 9 sag will be restored to its original value all other buses will be still under voltage sag experience .The result in figure 15, which clearly shows this effect on bus 9..

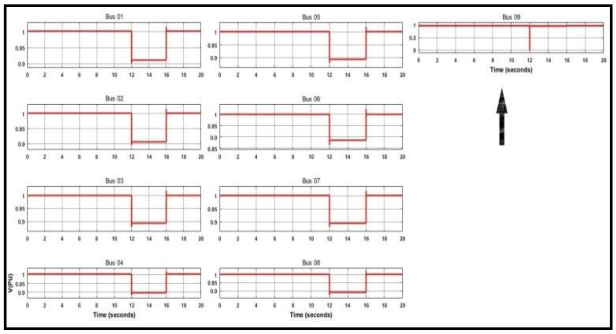

Figure 15. Voltage sag restore on bus 9

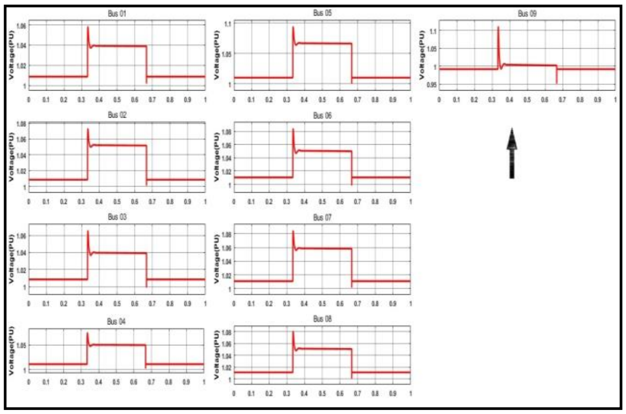

Figure 16. Voltage profile of 9 bus system during swell in which swell is restored on bus 9

When a 1000MVar capacitive load is connected to bus 5 through a circuit breaker which operates in 5 sec it create a voltage swell which affect all the buses .The system will undergo voltage swell and its performance badly effect. To enhance the system performance we implement a FACT device D-UPFC which is connected on bus 9 which suddenly restore the voltage that can be seen in the Figure 15, an arrow is indicating that bus.

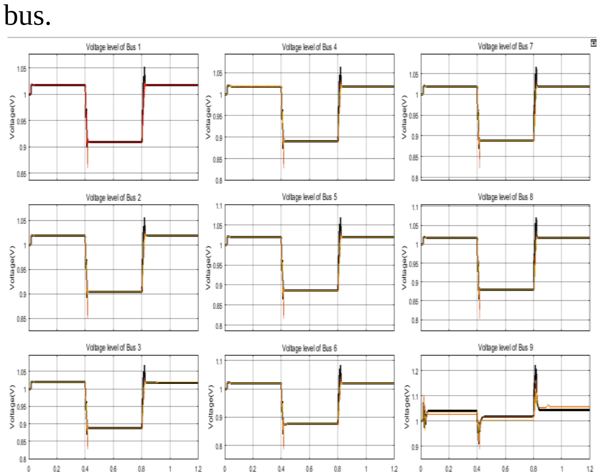

Figure 17. Voltage Sag in 9-Bus System & restored on Bus 9

5. Conclusion

The OLTC with fast transfer switching is easy to design and implement. It is low cost and easy control system rather than D-UPFC. The D-UPFC is a complex and difficult to design and implement. While installing in transmission line the phase angle and magnitude of D-UPFC is difficult and challenging task. The D-UPFC is a multifunction system which controls, voltage, phase angle, reactive power compensation etc. OLTC for voltage control of a single load with power factor improvement panel is better than D-UPFC. However during voltage sag OLTC increases voltage but the current also increases. It means that when a fault occurs in transmission or distribution system voltage sag occurs, so this voltage sag will increase when OLTC increase voltage. However for an infinite source and small size OLTC does not effect on voltage sag in primary side. OLTC is better to use for small load below than 10 MW. Micro grid system based on renewable energies i.e solar and wind etc, are currently increasing in the world. But these source have problems i.e. voltage and frequency instability. These problems can be avoided via fast transfer switch based on load tap changer to maintain voltage stability in the micro grid system. UPFC has advantages over OLTC for stabilizing of voltage and compensating of reactive power in the micro grid. 3 Phase OLTC can be used for 3 phase induction motors to avoid voltage instability. 3 Phase Fast transfer switch based OLTC can be used for starting of 3 phase induction motors. During starting the OLTC will be run in starting mode for this OLTC will be set on lowest Tap position as the motor speed increases the tap position will also change from lower to higher. When the motor reaches to its normal speed the OLTC will run in voltage control mode. Similarly a capacitor bank reactive power can be control via voltage control method using OLTC such as thyristor control reactor/capacitor.

6. Acknowledgment

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7. Abbreviations

A	Transformer Area (m^2)
B_M	Mutual Flux density (weber/m^2)
I_1	Transformer primary current (Ampere)
I_2	Transformer secondary current (Ampere)
I_F	Fault current (Ampere)
I_{LR}	Motor lock rotor current (Ampere)
I_P	Peak Inrush current (transformer)
I_S	Motor starting current (Ampere)
k	Transformation ratio
kVA	kilo Volt Ampere (Apparent power)
kVA_1	Short circuit Kva
kVA_2	Lock rotor kVA
kVA_r	Capacitor ratting
L	Inductance (Henry)
N_1	Transformer primary number of turns
N_2	Transformer secondary number of turns
$p.u$	Per Unit
R_1	Stater winding resistance (Ω)
R_2	Rotor winding resistance (Ω)
R_F	Fault resistance (Ω)
R_S	Series resistance (Ω)
RMS	Root mean square
S	Rotor slip (%)
V_1	Transformer primary voltage (Volt)
V_2	Transformer secondary voltage (Volt)
V_{LL}	Line to line voltage (Volt)
V_{LG}	Line to ground voltage (Volt)
X_1	Stater winding reactance (Ω)
X_2	Roter winding reactance (Ω)
X_F	Fault reactance (Ω)
X_S	Series reactance (Ω)
X_{Seq}	Source equivalent reactance (Ω)
X_T	Short circuit reactance (Ω)
Z_F	Fault impedance (Ω)
Z_S	Series Impedance (Ω)
$\Delta\Phi$	Phase angle shift (Degree)
Φ_M	Mutual flux (weber)
η	Efficiency (%)

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