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Smart Monitoring and Control of Tap Changer Using Intelligent Electronic Device

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Abstract**—**In this paper, monitoring and control of tap changer mechanism of a transformer implementation in an Intelligent Electronic Device (IED) is discussed. It has been a custom for decades to provide a separate panel for on load tap changer control for monitoring the tap position. However, this facility cannot either record or transfer the information to remote control centers. As there is a technology shift towards the smart grid protection and control standards, the need for implementing remote control and monitoring has necessitated the implementation of this feature in numerical relays. This paper deals with the programming, settings and logic implementation which is applicable to both IEC 61850 compatible and non-compatible IEDs thereby eliminating the need for separate tap changer control equipment. The monitoring mechanism has been implemented in a 28MVA, 110 /6.9kV transformer with 16 tap position with GE make T60 IED at Ultratech cement limited Gulbarga, Karnataka and is in successful service.

Keywords**—**Transformer protection, tap changer control, tap position monitoring, on load tap changer, intelligent electronic device (IED).

I. Introduction

TRANSFORMERS are the heart of the substation and the ever increasing power demand results in complicated interconnections facilitated by sub stations. Transformers convert the voltage and current from one level to another level, however the output of the transformer has to be maintained as a constant irrespective of the input to a certain level. This is an important requirement to ensure power quality and it is controlled by On Load Tap Changer (OLTC) mechanism. System voltage regulation would be challenged during failure of OLTC and monitoring of OLTC equipment is also a mandatory requirement to meet the smart grid standards. Existing method of achieving the voltage regulation is by installation of a panel called as OLTC panel, which can provide information of the system voltage along with the tap position indication. Suitable control mechanism is also adapted to raise or lower the tap changer during variations in system voltage. Conventional systems cannot communicate nor the proper functionality of the system be supervised from remote. Unmanned sub stations called as smart substations insists the need for remote communication and hence forces the implementation of this feature into an Intelligent Electronic Device (IED) which can monitor, control and further communicate on IEC 61850 standards. Implementation of this feature for a 28 MVA, 110/6.9 kV transformer at Ultratech cement limited Gulbarga, Karnataka is discussed in this paper.

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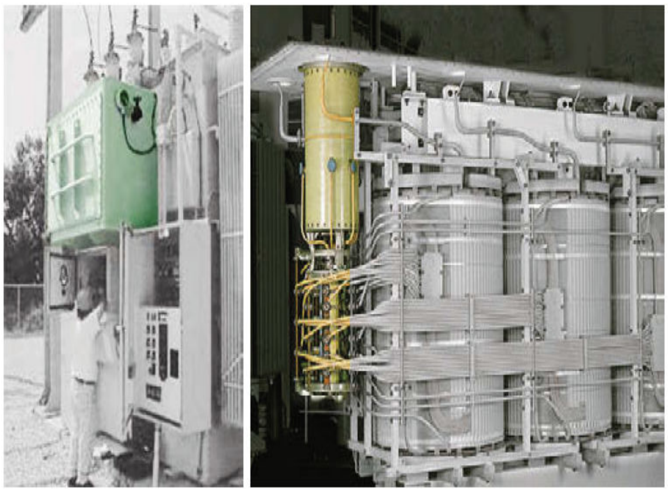
II. System Description

OLTCs used in transformers utilize two switching principles such as the high speed resistor type OLTCs and the reactor type OLTCs as shown in Fig. 1. Standards [1] have specified the operation and testing methodology of OLTC. Detailed explanation on the operation is available in literature [2] hence it is outside the scope of this paper. OLTCs continuously tend to maintain the system voltage by varying the tap positions by receiving raise or lower pulse from the control circuit.



a. Compartment Type b. In-tank type

Fig. 1 OLTC arrangements and types

In order to control the circuit, the current position of the tap changer has to be identified. Hence a mechanical to electrical conversion is required to monitor the tap position which is done using a transducer. Transducers are used to convert the position of the tap changer to a current output. It converts the measured quantities of resistance into a proportional load impendence DC signal. There are transducers designed dedicatedly for tap changer and therefore adjustable to meet the tap requirement for various transformer applications. The output signal can be connected to one or several receiving instruments such as panel indicators, recorders, controller, IEDs etc. It has a galvanic separation between input and output and auxiliary supply and they comply with IEC 688 standard. Fig. 2 shows the design of a transducer where a constant current is driven from the bridge amplifier to the measuring object. The voltage over Rx is amplified to a standard value which is galvanic ally separated from input in the insulating amplifier. The galvanic ally insulated measuring signal is converted to a load independent DC current in the output amplifier. The AC power supply comes from a transformer that gives a galvanic separation. Those parts that need separate power get it via a rectifying stage. The DC power comes from a switched unit that gives galvanic separation [3].

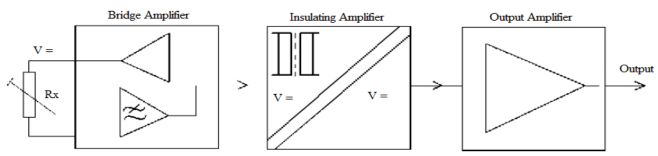


Fig. 2 Transducer working principle

The transducer used in this application provides a current output corresponding to the position of the tap changer as shown in Table I. This current is routed to the IED and the configuration of the IED for mapping it to the respective position is taken up in the next section.

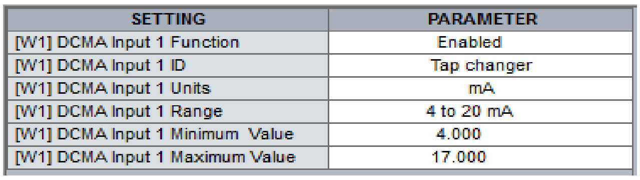
TABLE I
DCMA EQUIVALENT FOR TAP POSITION

TAP position	Current output of Transducer (DCMA)
1	0.060
2	0.120
3	0.180
4	0.240
5	0.300

III. IMPLEMENTATION OF MONITORING FEATURE IN IED

IEDs have the provision to accept direct current (dc) milli amps (mA) input which is wired to the relay from the external transducer. Fig. 3 shows the screen of the software which is used to configure the dcmA input in the IED. The setting provides the option to configure any user defined name and units, hence it provides the flexibility to configure any position indications for various applications. In this application, the name is configured as ‘Tap changer’ and the unit as mA since it is wired to the transducer.

In the relay, the value measured in mA has to be converted to pu value for configuration of the tap changer position logic. Table II shows the current measured by the transducer for the respective tap and the per unit (pu) conversion table. Column 2 is the measured value recorded from the transducer based on each tap position and column 3 is the corresponding pu value. The value thus obtained is configured in the flex element option available in T60 IED [4].



SETTING	PARAMETER
[W1] DCMA Input 1 Function	Enabled
[W1] DCMA Input 1 ID	Tap changer
[W1] DCMA Input 1 Units	mA
[W1] DCMA Input 1 Range	4 to 20 mA
[W1] DCMA Input 1 Minimum Value	4.000
[W1] DCMA Input 1 Maximum Value	17.000

Fig. 3 DCMA input of IEDs

TABLE II
DCMA PU CONVERSION FOR RESPECTIVE TAP POSITION

Tap	mA	pu
1	4	0.058
2	8.07	0.117
3	12.14	0.176
4	16.21	0.235
5	20.00	0.29

Flex Element is a universal comparator that can be used to monitor any analog actual value calculated by the relay or a net difference of any two analog actual values of the same type. The effective operating signal could be treated as a signed number or its absolute value could be used as per user's choice. The element can be programmed to respond either to a signal level or to a rate-of-change (delta) over a pre-defined period of time. The output operand is asserted when the operating signal is higher than a threshold or lower than a threshold as per user's choice. Detailed description on each and every setting is available in literature [5].

The values calculated in Table II are entered in the respective flex elements in the pickup cell and the corresponding tap position is given in the name cell. Depending on the tap position, the value of current increases and the flex element will pick up. If the transformer is in tap 1, then the current measured will be greater than 0.058 pu which in turn picks up flex element 1 and the IED will provide the position indication in the form of light emitting diodes (LED). If the tap is increased further to tap 2, then the current increases further resulting in a value greater than 0.117 pu. This will result in pickup of both flex element 1 and flex element 2. In order to provide the tap position as 2 instead of 1, an additional logic shown in Fig. 5 is incorporated. IEDs have an option to create user defined logic which provides the flexibility in the relay to adapt to any user defined application. The logics are assigned to virtual outputs (VO) which in turn can be assigned to any LED, output contacts or used as an input to the second logic. The application of this logic for tap changer position indication is discussed below.

When the tap was in position 1, flex element 1 alone will be high and the other flex elements will not ‘pick up’ since the current will not cross the ‘pick up’ settings of flex element 2 and above. This will ensure VO21 to be high, thus confirming the position as tap 1. If the tap is in position 2, flex element 1 and flex element 2 will be high and the other flex elements will not ‘pick up’ since the current will not cross the ‘pick up’ settings of flex element 3 and above. This will ensure VO22 to be high thus confirming the position as tap 2. In similar lines the logic is repeated and the IED will determine the correct tap position based on the logic. In Fig. 5, the logic used for 5 position indication is shown.

PARAMETER	FLEXELEMENTS 1	FLEXELEMENTS 2	FLEXELEMENTS 3
Function	Enabled	Enabled	Enabled
Name	TAP1	TAP2	TAP3
InputPlus	DCMA Ip1	DCMA Ip1	DCMA Ip1
InputMinus	OFF	OFF	OFF
InputMode	SIGNED	SIGNED	SIGNED
Compare Mode	LEVEL	LEVEL	LEVEL
Direction Type	OVER	OVER	OVER
Pickup	0.058 pu	0.117 pu	0.176 pu
Hysteresis	3.0 %	3.0 %	3.0 %
DeltaTUnits	Milliseconds	Milliseconds	Milliseconds
DeltaT	20	20	20
Pickup Delay	0.000 s	0.000 s	0.000 s
Reset Delay	0.000 s	0.000 s	0.000 s
Block	OFF	OFF	OFF
Target	Self-reset	Self-reset	Self-reset
Events	Enabled	Enabled	Enabled

Fig. 4 Flex element configuration of IEDs

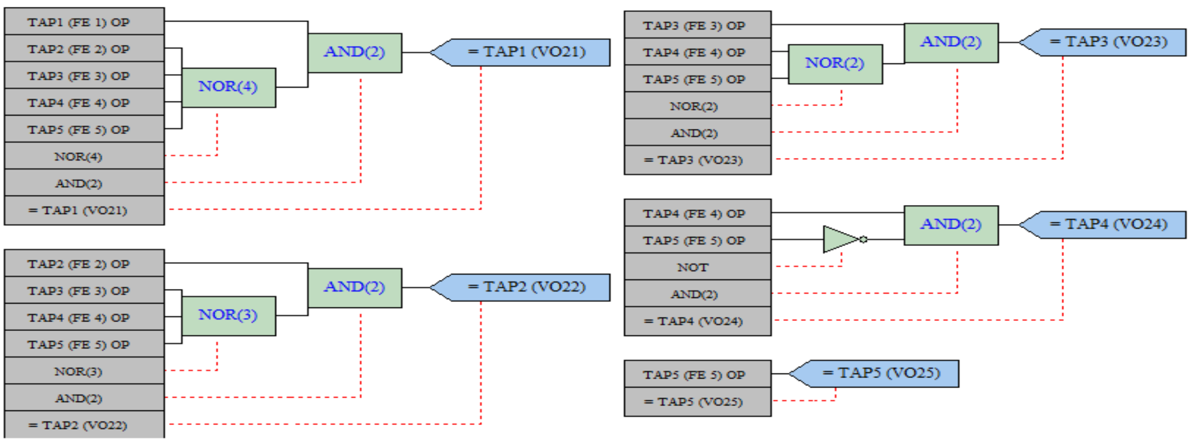


Fig. 5 Tap position indicator logic

With the combination of dcmA settings, flex elements and logic elements, the correct tap position is identified and the position is indicated in front of the relay using LEDs. T60 has 48 user configurable LEDs which can be used for this purpose. Thus the correct tap position is available to the user in front of the IED and at the same instance the information is recorded with time stamp and communicable with supervisory control and data acquisition (SCADA) system which is discussed in detail in section VI. Once the position is known, the next level of operation is to control the system voltage by varying the tap position. This control logic implementation is discussed in the next section.

IV. Implementation of Control Feature in IED

IEDs have many inbuilt protection functions, where under voltage (ANSI 27) and over voltage (ANSI 59) protection are utilized for this control operation [6]. These protection features have many stages and hence these functions can be used with a separate settings and timer apart from the one used for protecting the transformer. Fig. 5 shows the 27 and 59 protection element configured in the IED. The 27 element is used to supervise the voltage and it will be 'sealed in' if the voltage drops off below 0.95 pu after 1 second. The minimum voltage setting is used to supervise the breaker condition, thus the relay can differentiate between breaker closed and breaker open condition. If the potential transformer (PT) connected to the bus bar is used, then the minimum voltage setting will be configured as zero, as the voltage is not dependent on CB status. The 59 element will be 'sealed in' if the voltage crosses 1.05 pu after 1 second. Here, 1 pu refers to the nominal voltage of the transformer in the primary or in the secondary winding depending on the location of the PT. For example, if the PT is connected to the secondary of a 110/6.9 kV transformer, then 1 pu refers to 6.9 kV assuming 6.9 kV / 110V PT ratio, and the under / over voltage setting is 6.555 kV and 7.245 kV respectively. It is to be noted that these values are user configurable and varies based on application and requirement. These settings will allow the transformer secondary to vary between these two voltage values only and if it is exceeded on higher or lower side the tap changer control logic will be activated as described below.

PARAMETER	PHASE UV1
Function	Enabled
Signal Source	SRC 1 (SRC 1)
Mode	Phase to Ground
Pickup	0.950 pu
Curve	Definite Time
Delay	1.00 s
Minimum Voltage	0.100 pu
Block	OFF
Target	Self-reset
Events	Enabled

PARAMETER	PHASE OV1
Function	Enabled
Source	SRC 1 (SRC 1)
Pickup	1.050 pu
Delay	1.00 s
Reset Delay	1.00 s
Block	OFF
Target	Self-reset
Events	Enabled

Fig. 6 Voltage monitoring using inbuilt protection elements of IEDs

Fig. 7 shows the control logic implemented in the IED. When the system voltage reduces to less than 0.95 pu, the 'phase under voltage' protection feature 'pickup up' and 'set' 'reset' (SR) flip flop is 'set' thereby 'sealing in' VO41. The VO41 is in turn used to drive the contact output wired for 'tap raise' which is shown as P1 contact in the IED. This contact will initiate the 'tap raise' command to the OLTC and in parallel a timer is also initiated by VO41. At the end of the 'pick up' time of 10 seconds, the 'reset' signal of the SR flip flop becomes 'high' and it holds for 5 seconds based on the 'drop out' timer settings. The SR shown is a reset dominant configuration which means when both the 'set' and the 'reset' signals are high, then the output is zero, thus VO41 drops off after 10 seconds. The 'pick up' time of 10 seconds is the time duration given for the OLTC to operate and the voltage to stabilize. This timer can be modified based on the actual operation and voltage stabilizing time depending on the OLTC mechanism. After the VO41 drops off, the phase under voltage function will 'drop off' if the voltage is above 0.95 pu, else the 'set' signal will continue to be 'high', which in turn will again 'seal in' VO41 and the OLTC will be raised by another tap. The cycle will be repeated every 10 seconds and the taps will keep on raising till the voltage raises above 0.95 pu or till the OLTC reaches the maximum tap position. To prevent the logic from executing the raise command after the OLTC reaches the maximum tap, VO25 is included in the AND gate logic as shown. Tap 5 is the maximum tap discussed in this example which varies based on the total number of taps available. The similar logic with 'phase over voltage protection' element is used for lowering the tap as shown. Thus the tap changer control features becomes an inbuilt functionality of IEDs which acts as the building block for all IEC 61850 based application. In case of parallel operated transformers, the logic can be executed in one IED and the raise signal can be shared as generic object oriented substation event (GOOSE) information between the IEDs ensuring proper operation of all the transformers preventing circulating current issues [7].

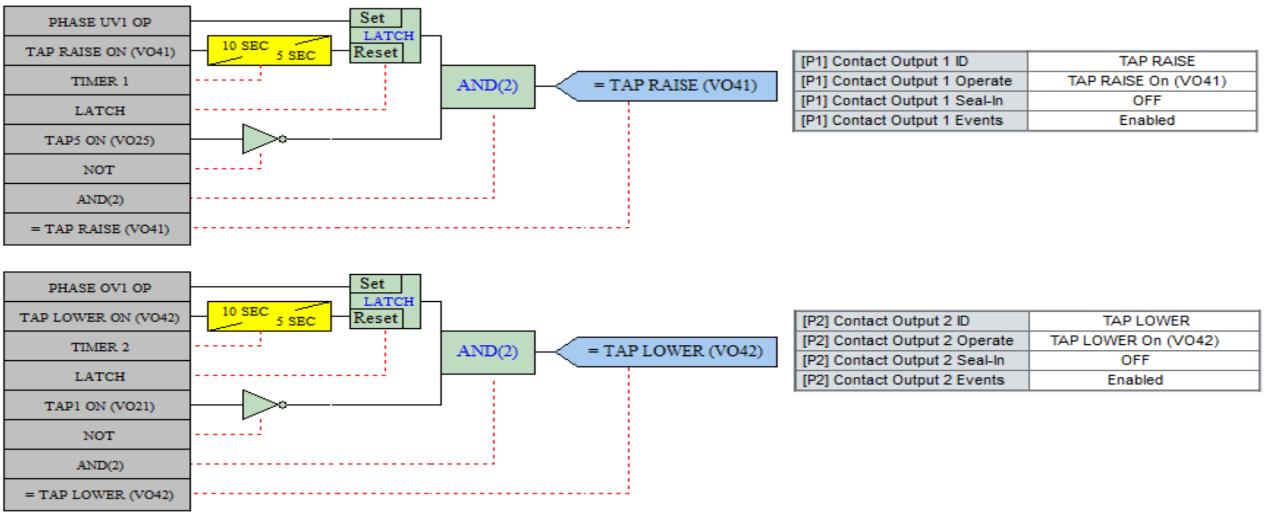


Fig. 7 Tap position control logic

The concept of 'master follower' used in parallel operation of transformers [8], [9] can be part of the IED which can be monitored and controlled from remote which is an essential part of smart grid. With the availability of monitoring and control feature incorporated in the IED, the next phase of automation is the tap changer counter which is discussed in the next section.

V. Tap Changer Counter Mechanism

Tap changer is a mechanical equipment which requires Periodic Over Hauling (POH) and the schedule between maintenance is decided by the number of operation that has been carried out when it was in service. This becomes a mandatory requirement for all the tap changers and hence it is manufactured with the counter mechanism [10]. The counter thus provided is available in the tap changer equipment as shown in Fig. 8. This counter is located in the switchyard and monitoring of this value from a load dispatch center requires additional equipment to convert it to digital from and a different protocol for communication. All these additional requirement can be eliminated by embedding it as a part of the IED which follows IEC 61850 standard.

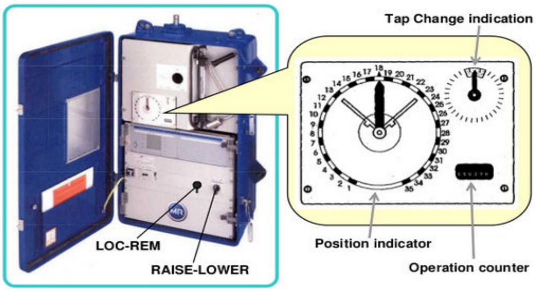
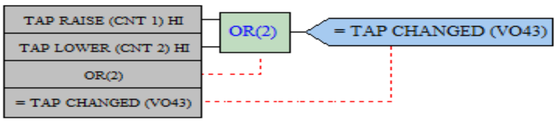


Fig. 8 Tap position operation counter indicator

In T60 IED, separate digital counters are available which can be utilized for this purpose. Fig. 9 shows the configuration of digital counter for tap changer counter application. Digital counter 1 and 2 is used for 'tap raise' and 'tap lower' signal respectively and digital counter 3 is for any operation. Digital counter 3 is triggered by an 'or' gate of digital counter 1 and 2. Hence digital counter 3 provides the total number of operations either in the raise or lower order which is used for POH calculation. These signals are already in digital form and thus can be communicated to any other relay or to SCADA for various applications. With the availability of information in the SCADA system, remote monitoring of tap changer and POH determination can be done in a simplified manner. Automatic annunciation can also be done if the indication reaches a specific value. The maximum number of counts that the digital counter supports is in the order of 2,147,483,647. With this capacity, tap changer operation can be counted very easily as the maximum operation limit for maintenance would be far less than the limit provided in the IED.

SETTING	PARAMETER
Digital Counter 1 Function	Enabled
Digital Counter 1 Name	Tap Raise
Digital Counter 1 Units	times
Digital Counter 1 Preset	0
Digital Counter 1 Compare	1
Digital Counter 1 Up	TAP RAISE On (VO41)
Digital Counter 1 Down	OFF
Digital Counter 1 Block	OFF
Digital Counter 1 Set To Preset	OFF
Digital Counter 1 Reset	OFF
Digital Counter 1 Freeze/Reset	OFF
Digital Counter 1 Freeze/Count	OFF

SETTING	PARAMETER
Digital Counter 2 Function	Enabled
Digital Counter 2 Name	Tap Lower
Digital Counter 2 Units	times
Digital Counter 2 Preset	0
Digital Counter 2 Compare	1
Digital Counter 2 Up	TAP LOWER On (VO42)
Digital Counter 2 Down	OFF
Digital Counter 2 Block	OFF
Digital Counter 2 Set To Preset	OFF
Digital Counter 2 Reset	OFF
Digital Counter 2 Freeze/Reset	OFF
Digital Counter 2 Freeze/Count	OFF



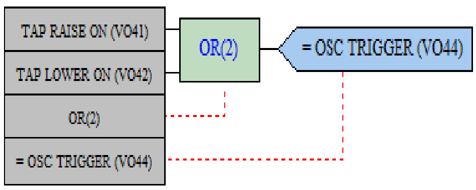
SETTING	PARAMETER
Digital Counter 3 Function	Enabled
Digital Counter 3 Name	Tap Changed
Digital Counter 3 Units	times
Digital Counter 3 Preset	0
Digital Counter 3 Compare	1
Digital Counter 3 Up	TAP CHANGED On (VO43)
Digital Counter 3 Down	OFF
Digital Counter 3 Block	OFF
Digital Counter 3 Set To Preset	OFF
Digital Counter 3 Reset	OFF
Digital Counter 3 Freeze/Reset	OFF
Digital Counter 3 Freeze/Count	OFF

Fig. 9 Digital counter configuration in T60 IED

In this manner, the tap changer counter feature is incorporated in the IED. The inbuilt features for post fault analysis like events and waveforms can also be triggered for system study purpose which is detailed in the coming section.

VI. Events and Waveform Trigger for Change in Tap Position

Events and waveform are the most important parameters for system study and fault analysis. In case of voltage fluctuation resulting in OLTC operation, we can only monitor and control the system with the existing equipment. In IEDs, features such as events and waveform are available to record the analog and digital values with exact time stamp with mille second (ms) accuracy. IEDs support time synchronization with GPS as defined in standard like, IRIG-B, SNTP, IEEE 1588 [11]. When there is an actual fault and the relay operates, the position of the tap is also available as additional information which was not available earlier. The trigger criterion for recording the waveform is shown in Fig. 10.



SETTING	PARAMETER
Number Of Records	15
Trigger Mode	Automatic Overwrite
Trigger Position	50 %
Trigger Source	OSC TRIGGER On (VO44)
AC Input Waveforms	64 samples/cycle

Fig. 10 Waveform Trigger for Tap position indicator

VII. Conclusion

This paper presents the most effective ways of monitoring and controlling the OLTC equipment. Modern IEDs have enhanced features and they are the fundamental building blocks of smart grid system. OLTC controller designed with such IEDs will provide all the benefits applicable for smart sub stations and provide additional benefits for fault analysis and system study. The existing system suffers the dis advantage of remote monitoring and supervision which has been eliminated by the use of a novel solution discussed in this paper which has been engineered and appropriate configurations have been implemented in the IEDs. The system has been commissioned since June 2014 and running successfully.

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