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An alternative design and implementation of a solid state on-load tap changer

Abstract

Power quality and reliability are of great importance in the modern world. Power utilities and customers are often concerned with the quality and reliable nature of power supply, whether it be the power generated by the power utilities or the power consumed by the customer respectively. They need these supplies to be at its optimum value so that the cost is effective, and the safety of devices assured otherwise problems such as overvoltage, under-voltage, and voltage sags caused by disturbances in the power supply could be disastrous. On-load tap changers (OLTC) have therefore been used since the inception of electrical engineering. The main function of the OLTC is to change the turns of the transformer winding so that the voltage variations are limited without interrupting the secondary current. In earlier days, mechanical types of on-load tap changers also known as under load tap changers (ULTC) were used but they had considerable limitations and drawbacks such as arcing which is mostly predominant, high maintenance, service cost, and slow response or reaction time. Fast switching power electronic semiconductor devices like triacs, IGBTs, MOSFETs, GTOs, and thyristors have made problems associated with mechanical on-load tap changers primarily rectified. The major idea is that the electronic switches and other smart systems provide more controllability during the tap changing process, unlike mechanical switches. This paper presents an alternative design and implementation of a low-cost solid-state OLTC and employs a control strategy that is microcontroller-based, ensuring the desired flexibility and controllability required in programming the control algorithms. It eliminates the limitations of both mechanical and hybrid OLTCs (arcing, slow response time, losses) and is user-friendly (provides an effective communication medium). Voltage regulation is achieved by varying the turns of the transformer winding while it is energized, supplying load current and with the tap selection carried out on the primary side. Therefore, this approach provides a less expensive system but ensures the efficiency and reliability of voltage regulation.

Keywords: on-load tap changer; solid-state switch; potential transformer winding; voltage regulation.

I. Introduction

The role of the power utility is not just limited to providing power supply to the customer but also to ensuring good quality and reliability with minimum disruptions in terms of overvoltage, under-voltage, imbalance, noise, and harmonics [1]. These disturbances are undesirable to most industrial and commercial end-users since they have dire economic implications. Voltage regulators, capacitors, and dc stored energy systems amongst others have been employed to rectify these problems. The most popular agent for controlling voltage levels at the distribution and transmission

systems is the on-load tap changer transformer. The OLTC has therefore been widely used since the introduction of electrical energy [2]. Tap changers are generally divided into three categories depending on their method of operation; off circuit tap changer, offload tap changer and on-load tap changer [3]. The latter is preferable as there is no disconnection of the transformer when changing the tap setting, thus the operation of supplying the load demand remains uninterrupted. Several on-load tap changing systems exist. Among these are mechanical, electronically assisted (hybrid), and fully electronic (solid-state) types. The mechanical and

electronically assisted types have considerable drawbacks such as arcing, high maintenance, service cost, and slow response time [4]. Hence, system reliability is reduced.

However, to eliminate these shortcomings, alternative configurations have been introduced which improve the reliability of the system. To date, the proposed constructions have been able to eliminate arc formation using a tap changer where quick operation is desirable. In such a case, the fully electronic (solid-state) tap changer provides the flexibility, controllability, and reliability desired.

On-load tap changing involves techniques to sense voltage variations and relay this information to an appropriate device for decisions to be taken. The essential nature of the information obtained from this activity has prompted a few studies aimed at developing systems for solid-state on-load tap changing with a handful of prototypes developed. Some of these solid states on-load tap changing systems have been developed for use in medium voltage (MV) systems, [5][6]. Similarly, in [7][8], solid state OLTCs are used to mitigate MV system losses. In [9][10], also employ solid state devices in low voltage (LV) distribution systems for on-load tap changing. In [11][12], a microcontroller is utilized for control operations. OLTCs lessen voltage sags in LV systems with power semiconductor devices [13][14].

A. K. Gamit showcases a design that maintains the desired load voltage irrespective of input voltage variations [15]. This system has thyristor switched taps on the High Voltage (HV) side of the transformer and the load on the Low Voltage (LV) side. Load voltage variations are sensed by the

microcontroller and the value compared with a reference. This gives the command to trigger the appropriate antiparallel thyristor for the needed tap selection.

Rao et al. and Thakare et al. present a system that regulates voltage using static OLTC with sequential controllers [16][17]. This model has GTO switched taps on the primary side and a load connected to the secondary side of a transformer. The load voltage was measured, compared with the pre-set value and an error value obtained. Error values found outside the dead band gave a lower or higher correction after a pre-determined delay else no operative action was taken. This process continued until the load voltage was within the inner dead band. The delay in tap selection as a result of this process makes it less reliable.

A work conducted by [18] employed the use of thyristors for tap changing. The thyristors tap changer system used two antiparallel thyristors for each tap in a single phase operation. Voltage selection was achieved when one group of antiparallel thyristors were turned on and the others off. Transitioning from one tap to the other downwards was problematic as a short circuit could occur and damage the system in case of a wrong switching sequence which renders the system inefficient. Additionally, the thyristor/GTO model which resolved the switching problem needed extra circuitry which resulted in high costs.

Kavad et al. and Pota et al. model offer a system that has a microcontroller that controls the tap selection on the secondary side of the transformer based on the transformer output voltage [19][20]. The tap changing on the secondary side of the transformer leaves the system vulnerable to arcing since tap selection at the

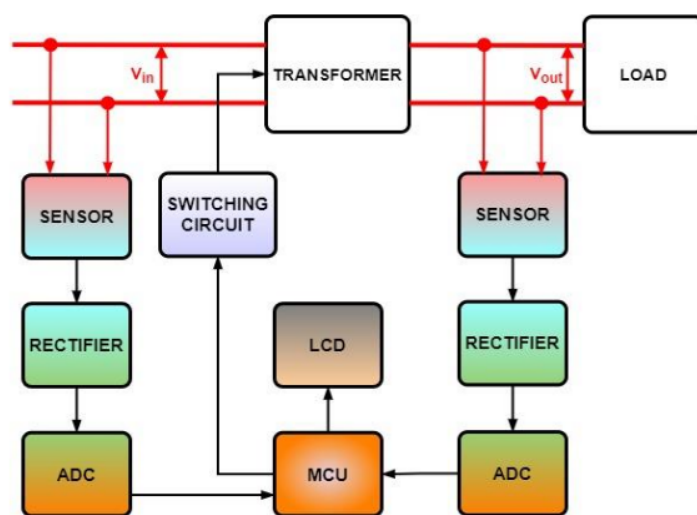


Figure 1. Block diagram of proposed system architecture

secondary side produces high current resulting in sparks which slightly increases cost [21][22].

II. Materials and Methods

A. Proposed system design and architecture

The presented solid state on-load tap changer consists of three (3) primary and 2 secondary units as represented in Figure 1. These are the Transformer Unit (TU), Switching Unit (SU), the Microcontroller System Communication Unit (MSCU), the Display Unit (DU) and the Signal Sensing, Conversion and Rectification Unit (SSCRU). The SU which employs solid state static switches were connected to the control unit of the microcontroller and to the taps on the primary side of the transformer as illustrated.

Potential transformers and rectifiers were used as sensors to step down voltages from the input and output of the main transformer which were fed to the ADC of the microcontroller simultaneously. The microcontroller is responsible for converting the analog signals into digital values for processing. The DU which was interfaced with the microcontroller projected numerically the input and load voltages as well as the voltage drops. The SU, ADC, LCD and the microcontroller were powered by an independent or auxiliary power supply.

1) The transformer unit (TU)

The transformer operates on the law of electromagnetic induction (EMI). The EMI is defined as the production of an electromotive force (EMF) across an electrical conductor in a changing magnetic field. The conductors used in transformer cores are wound several times. Several connections brought outside from any points between the terminals of the transformer winding with appropriate distancing were transformer tapings. These taps are principally used for voltage control mechanisms and were located on either side of the transformer. Based on the transformer EMF equation given by.

$$\frac{E_2}{E_1} = \frac{N_2}{N_1} = K \quad (1)$$

where E_2 and E_1 are the secondary and primary voltages, N_2 and N_1 the secondary and primary turns respectively and K the turns ratio.

From equation (1), it is observed that varying the number of turns affects the desired voltage. Therefore, to maintain a constant secondary voltage irrespective of the primary voltage, the primary turns were varied to change the turns ratio. This was the tap-changing

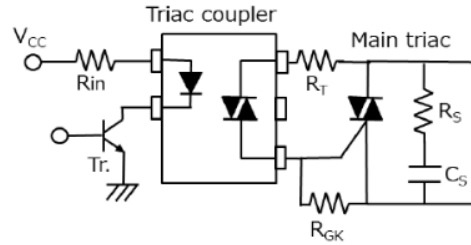


Figure 2. Pictorial and circuit view of the triac driver or opto-isolator [23]

concept. The KNUST laboratory's single-phase transformer with five taps was used as the TU.

2) The switching unit (SU)

The SU uses static solid-state power switches. The choice of switch, working principles, and position on the transformer were factors considered in the design process to achieve efficiency at a minimal cost. There are several static switches employed in AC switching. However, the choice of switch used in the implementation of this project was a triac with a zero-crossing optically isolator or triac driver. The factors that accounted for the choice were the cost, response time, forward voltage drop, losses, the durability of the switch, and the operation voltage of the transformer. The triacs were attached to heat sinks or dissipating brackets to ensure safety when driving the load. The triac driver or opto-isolator employed in this system adds a desirable feature of isolation and protection. It interfaces between the microcontroller and triacs to control resistive and inductive loads in AC operation. The pictorial and circuit view of the triac driver or coupler is shown in Figure 2.

As depicted in Figure 2, the triac driver houses an LED, optically triggered triac, zero-crossing detector, and a snubber capacitor. A high signal received at a pin glows the LED which then triggers the internal triac. The internal triac subsequently receives a gate pulse and connects it to the 240V end. The zero-crossing provided was primarily to drive resistive loads to ensure minimal switching losses and interferences injected into the supply. The snubber circuit having the resistor (R_s) and capacitor (C_s) was attached to suppress reverse voltage and control the rate of rising at the turn-off to prevent dv/dt retriggering when operating inductive loads. The additional benefit was to reduce radiated noise.

Current flows through the snubber circuit in the event of a sudden voltage spike dv/dt . The snubber capacitor C_s suppresses dv/dt while R_s prevents device failure due to discharge current from C_s when the triac switches on. A 40Ω

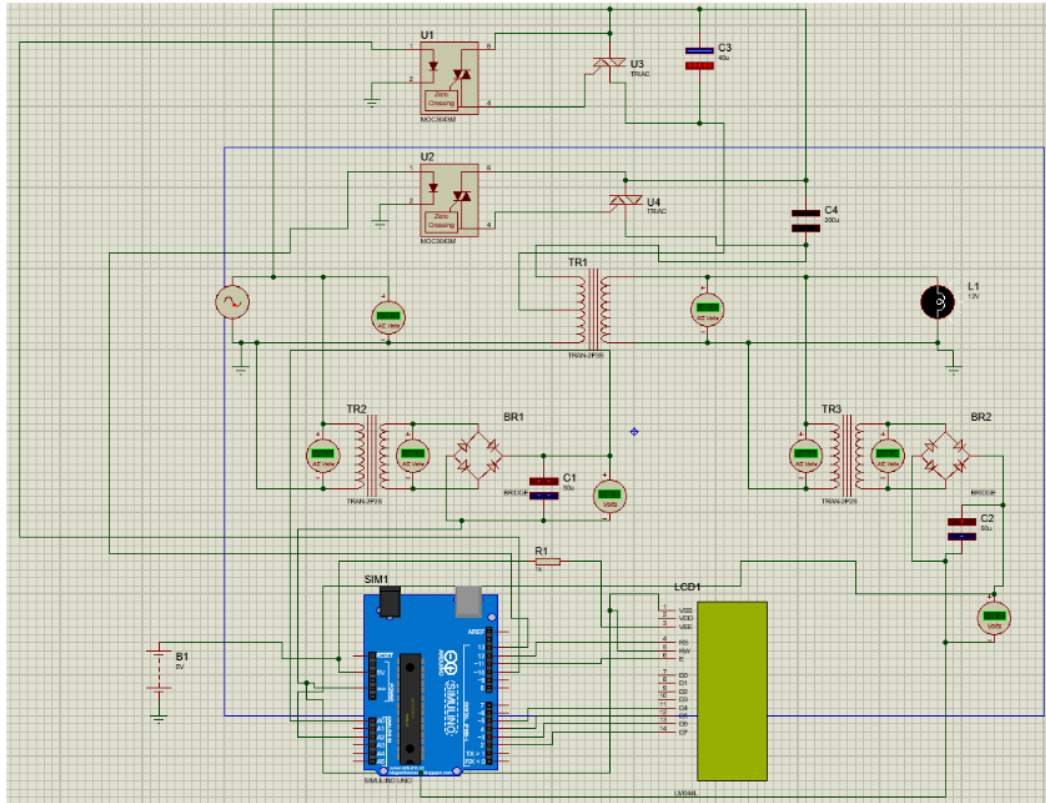


Figure 3. Circuit diagram with all components

maximum resistance and $0.01\mu\text{F}$ C_s were generally considered for 100V AC power. The charging time (T) of the snubber capacitor is given by the expression [23]:

$$T = C_s \cdot (R_L + R_s) \quad (2)$$

where R_L is the load resistance.

3) Microcontroller system communication unit (MSCU)

The MSCU uses a microcontroller interfaced with an LCD to ensure quality and effective communication. The microcontroller was used as the logical central process control unit to process the input signals and produce a suitable output signal according to the program loaded onto it. It has ADC's which are used for converting rectified analog input and output voltages. These voltages are received as high signals by the microcontroller through its ADC pins where they are converted to digital values. Based on the program loaded on the microcontroller, decisions are made as to which tap must be selected on the transformer to ensure constant load voltage supply. Since the SU was directly connected to the high voltage side of the transformer [24], we can protect the microcontroller from

exposure to high voltages with triac drivers or opto-isolator [25].

The LCD which is essentially the output device was used to showcase the decisions made by the microcontroller in text and numerical format. It shows the input and output voltages recorded, the tap selected, and the system's voltage drops. This was needed to provide easy data collection. Accurate data transmission to the display is ensured due to the wired connection employed in the system communicating with the microcontroller.

B. Circuit illustration and flow chart

The presented solid-state on-load tap changer components in Figure 1 were illustrated in circuit form using Proteus professional design and simulation tool. Represented in the circuit in Figure 3 are the Transformer Unit (TU), Control Unit (CU), Switching Unit (SU), Display Unit (DU) and the auxiliary power supply. The transformer unit (TR1) that was used for the simulation had only two taps whose terminals were connected to the triacs. This subsequently reveals the number of triacs (U3, U4) and triac drivers or opto-isolators (U1, U2) that were employed in the switching process. The transformers (TR2, TR3) were involved to

step down the input and output alternating current (AC) voltages for the microcontroller action. Bridge rectifiers (BR1, BR2) and capacitors (C1, C2) were used to convert ac to dc and to smoothen the dc respectively. The auxiliary power supply source (B1) provides the dc needed to power the microcontroller and display. The microcontroller (SIM1) receives the analog input and load voltages through the analog pins, convert the values into digital forms using the ADC and produces a suitable output signal based on the loaded program. A pulse is then authorized to the selected triac through the triac drivers for appropriate tap selection.

In Figure 4 is a view of the flow chart showing the schemes of operation of the solid-state on-load tap changer. It begins with the initialization of the program as well as the display. Any voltage sampled between 15-20V results in the selection of Tap 1 to ensure a constant output voltage else the microcontroller continues to sample voltages between 21-39V, 40-57V, and 58-65V where other corresponding Tap may be selected. This cycle continues until an appropriate Tap is selected. Sampled voltages above 65V result in a break to this program cycle.

III. Results and Discussions

A prototype of the single-phase solid state on-load tap changer comprising of the transformer, switching, microcontroller, and display unit was set up in the KNUST laboratory. The prototype was subjected to testing in a

Table 1.
Input voltages with corresponding selected taps and nominal load voltage values

Condition	Input Voltage	Output Voltage	Tap Number
Nominal	15 V - 20 V	5 V	Tap 1
	21 V - 39 V	5 V	Tap 1
	40 V - 57 V	5 V	Tap 1
	58 V - 65 V	5 V	Tap 4

laboratory environment to achieve precise simulation of the real-life setting. Figure 5 shows the prototype test setup.

The primary of the transformer was connected to a 240V rms input voltage and with the aid of a variac, various voltage variations were achieved. The triacs connected to the corresponding taps were triggered by a high signal from the microcontroller to select a particular tap based on the program or algorithm loaded under different voltage situations.

The circuit was tested with a 2kVA power transformer having four taps; Taps 1, 2, 3, and 4. Four tests were run on the circuit to determine proof of concept and performance. In these tests, the input and output voltages of the power transformer were manually measured with a voltmeter and compared with the displayed voltages from the microcontroller. A nominal voltage of 5V with a tolerance of $\pm 1.5V$ was expected to drive the motor load connected across the secondary side of the transformer. At this condition Tap 1 was active or on. The results of the tests are summarized in Table 1.



Figure 5. Test setup of prototype

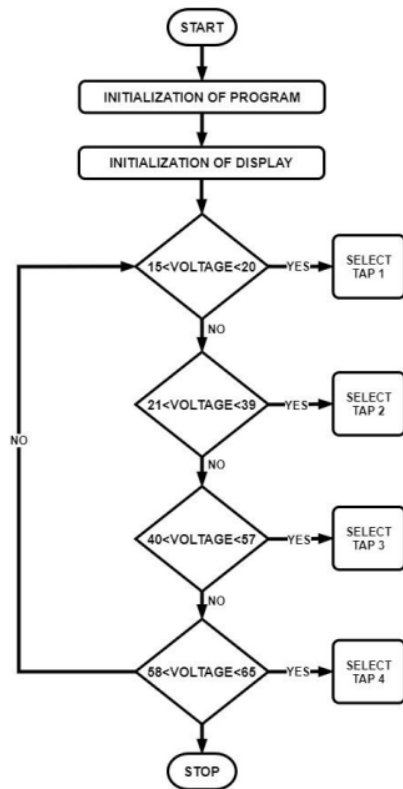


Figure 4. Interaction of forces in the APF

The prototype was tested for reliability by measuring the output or load voltage of the transformer when the input voltage was increased steadily. From the table, as the input voltage increased above the nominal, the microcontroller generated a pulse which increased the tap setting by one (changing from Tap 1 to Tap 2) to maintain the load voltage at nominal value. The microcontroller continued to monitor the input voltage and once it fell within the desired range, the appropriate tap was selected, and the cycle continued to loop. The microcontroller managed to maintain the load at its nominal voltage within its specified value of $5 \pm 1.5V$ and it was shown to be reliable. Figure 6 and Figure 7 show pictures of the OLTC prototype setup.

An additional system test was conducted which involved higher voltage ranges above 100 V. After the test, two triacs which controlled Taps 3 and 4 were damaged. This was attributed to protection related issues.

IV. Conclusion

In this paper, we have proposed and tested a system for on-load tap changing on single phase power transformers. Based on theoretical and empirical

results, the system maintained a nominal load voltage despite input voltage variations. This proves that the solid-state on-load tap changer differentiates between transformer taps. A system is therefore a viable option for on-load tap changing.

Compared to other on-load tap changing systems, it is more effective, accurate, and cost-effective. The control and switching system employed in this system eliminates arcing, contact wear since there are no movable parts, and reduces maintenance cost, and improves switching time and system safety and stability. The designed system was highly practical and adaptable for LV installations. It can be used to maintain voltage levels in an electrical system given the needed system protection.

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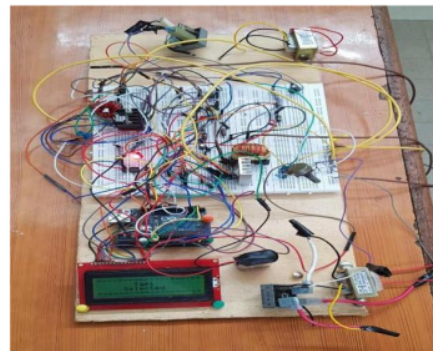


Figure 6. A view of the setup showing Tap 1 selected on LCD display with an LED glow indicator

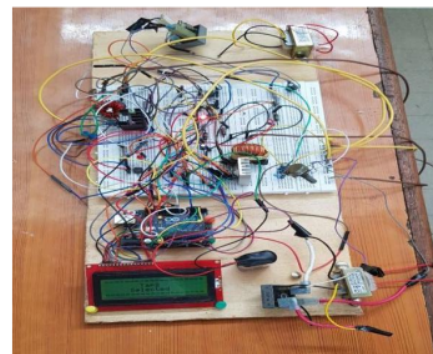


Figure 7. Another view of the setup indicating Tap 2 selected with a corresponding LED glow

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