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# OPERATIONS AND CONTROL OF SMART TRANSFORMER FOR MANAGERIAL PERFORMANCE OF STAND-ALONE OPERATIONS

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Keywords:

*Smart transformer; Stand-alone; Distributed energies; Special load demand; Rural and remote area electrification.*

A B S T R A C T

*Power transformers form very delicate and salient part of changing voltage and current levels to suite power transferability and distributions in the power grid system. As smart transformer is the main driving component of this fast growing smart power grid system serving the capacity of delivering quality, efficient and reliable power to meet the resent dynamism in load demand and various system applications. Discussed in this paper is how smart transformer helps in the integration of distributed energies for stand-alone applications such as supplying power to rural and remote areas, special load applications. Therefore MATLAB software simulated and analyzed the operational control of smart transformer for stand-alone application aiming at using two distributed energy sources (Small hydro-dam and wind energy). Also elucidated in this paper is how judicious these distributed energies would be controlled and operated to distribute quality, reliable, secured and cost effective power supply for stand-alone purposes.*



## 1. INTRODUCTION

Considerably, around 70 percent of the population in Sub-Saharan Africa lacks access to electricity and 85 percent of them reside in rural areas, while about 50 percent in South Asia do not have access to electricity. Rural and remote area electrification; as of recent has become a prodigious challenge in the power industry as there are high demands of electrical energy in the urban areas. In addition, industrialization, and advancement of technology in the urban areas, expensive cost of long transmission lines and high transmission losses contribute significantly to the lack of power supply to meet the demands of special applications, rural and remote areas. Statistics shows that 85 percent of more than 1.4 billion people without access to electricity come from rural areas (Zomers et al., 2011).

The world population is expected to rise by 2.3 billion between 2011 and 2050, from 7.0 billion to 9.3 billion (UN, 2011) and also stipulated sustainable energy for all under the auspices of the UN's sustainable goal 7 by 2030. Therefore it's pertinent for research to be done to provide optimum solutions to curb these problems facing the power industry. Hence discussed in this paper is the Matlab simulation and analysis of operational control of smart transformer for stand-alone applications.

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Smart transformer is the main driving component of this fast growing smart power grid system serving the capacity of delivering quality, efficient and reliable power to meet the resent dynamism in load demand and various system applications. Smart transformer helps in the integration of distributed energies such as small hydro-dam, solar energy, wind energy, geothermal and tidal energy which can be used to serve the purpose of stand-alone applications; thus using the smart transformer to distribute power to locations (rural and remote areas) very far from the main power grid and for special load demands like military application.

In the simulation, an alternative to the CT in the distribution grid system was suggested as an intelligent (ST) transformer. The Smart Transformer's main component structure is made up of three-stage power converters, control and communication points. The first stage is the AC-DC rectifier, the second is the DC-DC chopper, and the third stage is the DC-AC converter (inverter) for stand-alone applications connected to the AC distribution lines. It also has the control features from the dc-dc link point to supply Dc voltage to special load for military equipments and hospital equipments within the locality. Additionally, the ST provides benefits such as voltage transformation and insulation between rectifier and inverter sides like the CT, the ST may provide many additional features such as balanced sinusoidal voltage in stand-alone distribution system and a balanced sinusoidal unit power factor current on the distribution side since its able to integrate other distributed energies (DEGs). The simulation shows power distribution system consisting of two radial feeders, one feeder connected to the conventional transformer and the other connected to the proposed smart transformer in a rural and remote area.

Synoptically, the paper elucidates the operational control features of the smart transformer to enhance cost effective, quality, secured and reliable power distribution for stand-alone and special load application.

## 2. OPERATION OF CONVENTIONAL TRANSFORMER

The traditional transformers are clearly isolating and voltage processing devices that form a vital component of an electric power distribution system, which begins service for more than hundred years, because their electrical transformation without moving parts normally is used to move electrical power from one circuit to the other through electromagnetic inductance. The analyses recorded in numerous research papers indicate, however, clearly massive negative effects on human health and the ecological environment as a whole of this traditional transformer (Budu & Ram, 2020). This sub-section explains how conventional transformer is used for stand-alone application and its limitations compared to the proposed smart transformer.

Fig.1 clearly illustrates the traditional way of supplying power for stand-alone load distributions; thus,

i. Generation from a small hydro-dam
ii. Then transmitted to various sub-stations
iii. Voltage stepped down by the conventional transformer for stand-alone load demands
iv. Applications of various compensation devices (STATCOM, APF, etc).

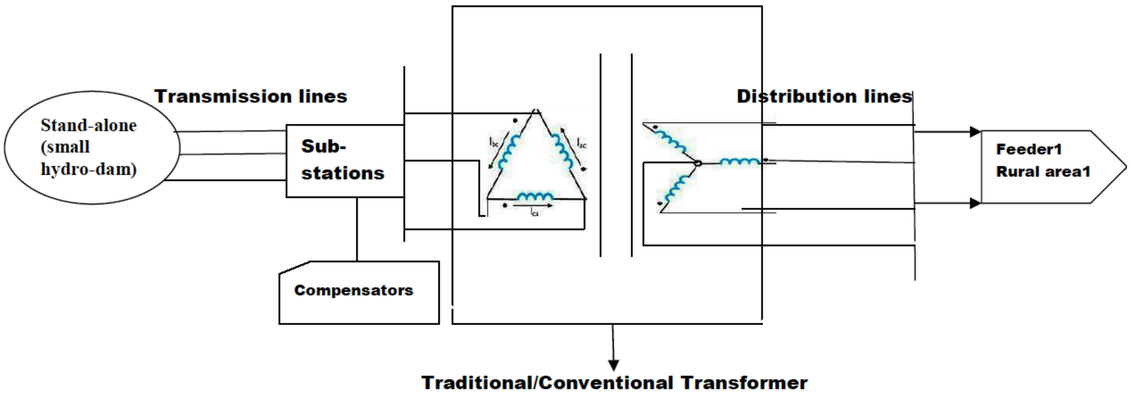


**Figure1.** Line diagram of CT for stand-alone application

### 2.1 Load and Frequency Control

Load and frequency control is pre-eminent for voltage stability in the power system of which the transformer plays a major role. The below figures illustrate how conventional transformer in it tradition way control the load and frequency for stand-alone applications; thus controlling the load and frequency of remote or rural area. Using a software for the simulation, the following values would be considered as shown in table 1.

**Table1.** Parameters for transfer function model

| Parameter | Value |
|---|---|
| Tg | 0.4 |
| Tt | 0.5 |
| Kp | 100 |
| Tp | 20 |
| R | 3 |

Shown in fig. 2 is the transfer function illustration of how load and frequency are controlled for a specific area. The diagram depicts how the small hydro power plant generates voltage for supply based on load control by the conventional transformer. Small load change results in a major favorable controller output response, hence for the conventional transformer to keep a synchronized power from the turbine to the generator, normally tap changers are automatically or manually used regulate the change in load aiming at minimizing temporal variance and ensures that steady state errors after load change are reduced to zero.

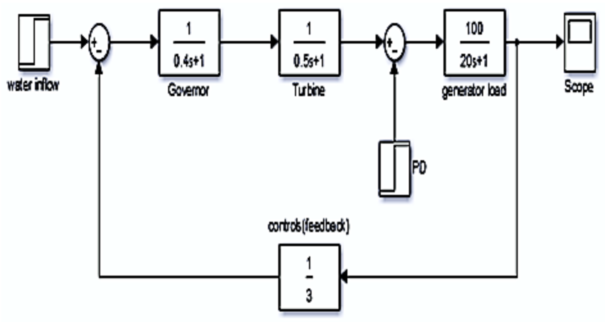


**Figure 2.** Transfer function model of controlling load and frequency

Mathematically;

$$\frac{D}{dt}(\Delta f) = \frac{1}{Tps}[-\Delta f + Kps\Delta Pg - Kps\Delta Pd] \quad (1)$$

$$\frac{D}{dt}(\Delta Xe) = \frac{1}{Tsg}[-\Delta Xe + \Delta Pc - \Delta f/R] \quad (2)$$

$$\frac{D}{dt}(\Delta Pg) = \frac{1}{Tt}[-\Delta Pg + \Delta Xe] \quad (3)$$

Where;
$\Delta f$ = change in frequency
Tps = constant time of power system
Kps = gain of power system
$\Delta Pg$ = change in power gain
$\Delta Pd$ = change in load demand
Xe = system impedance
Tt = constant time of turbine (Shah & Kotwal, 2012).

## 2.2 Voltage and Current Control

Frequency and load optimal control basically helps the power system for a given application to control, stabilize any disturbance and enhance the voltage profile of the power supply. Costs have been significantly affected by the use of various turbines to put more power in the grid. This lack of energy contributed to regular load shedding, with load shedding costs six times higher than operating turbines (Abban & Bhagwan, 2020). The model below explains how conventional transformer is used for stand-alone application and its limitations compared the smart transformer.

**Table 2.** Parameters for CT

| Parameters | Values |
|---|---|
| Nominal power and frequency[ Pn (VA) , fn(Hz)] | 250MW , 50 |
| Primary Winding [ V1 Ph-Ph(Vrms) , R1(pu) , L1(pu) ] | 33kW,0. 002, 0.08 |
| Secondary Winding [ V2 Ph-Ph(Vrms) , R2(pu) , L2(pu) ] | 11kW, 0.002 , 0.08 |
| Magnetization resistance Rm (pu) | 500 |
| Magnetization inductance Lm (pu) | 500 |

**Table 3.** Load Parameters

| Parameters | Values |
|---|---|
| Nominal-phase-to-phase voltage Vn (Vrms) | 440 |
| Nominal frequency fn (Hz | 50 |
| Active power P (W) | 10kW |

The Simulink block model in fig. 3 explains the control principle of current and voltage by a conventional transformer for stand-alone application in a rural or remote area.

### A. Stand-alone Generation Station

Normally the traditional source of generation for stand-alone power distribution is by using small hydro power plants, thermal and geothermal power plants.

Other renewable such as solar, wind energy could be integrated by using separate inverters for converting the DC source to AC source before the conventional transformer can distribute to the various rural/remote and other special load applications.

### B. CT for Power Distributions

Currently the conventional transformer is used for only AC voltage distribution with about 75%-80% efficiency of the power generated. The following are the major components of the conventional transformer:

i. **Core:** the core of the CT is used as a supportive system for both the primary and secondary windings of the transformer.
ii. **Windings:** it constitute several copper coils connected to form a complete turns. We have the primary windings for voltage input and the secondary windings for voltage output.
iii. **Insulating material:** materials like paper, transformer oil and card boards are normally used to isolate the core of the transformer, both the primary and secondary windings.
iv. **Conservator tank:** its airtight metallic cylindrical tank fitted above the CT to conserve the transformer oil.

v. **Breather:** cylindrical container filled with silica gel for absorbing the moisture in the tank to avoid penetration of moisture in the insulating oil.
vi. **Tap changers:** these are normally mechanical devices for balancing voltage variations with respect to the change in load demand. We have On-load and Off-load tap changers.
vii. **Buchholz Relay:** it operates by gases emitted due to decomposition of the transformer oil during internal faults. It's used to sense and in turns protect the transformer from internal faults.
viii. **Explosion vent:** is used to expel hot temperature from the transformer during internal faults to avoid explosion.
ix. **Cooling Tubes:** by natural or forced means, the cooling tubes provide paths which are used to cool the transformer oil.

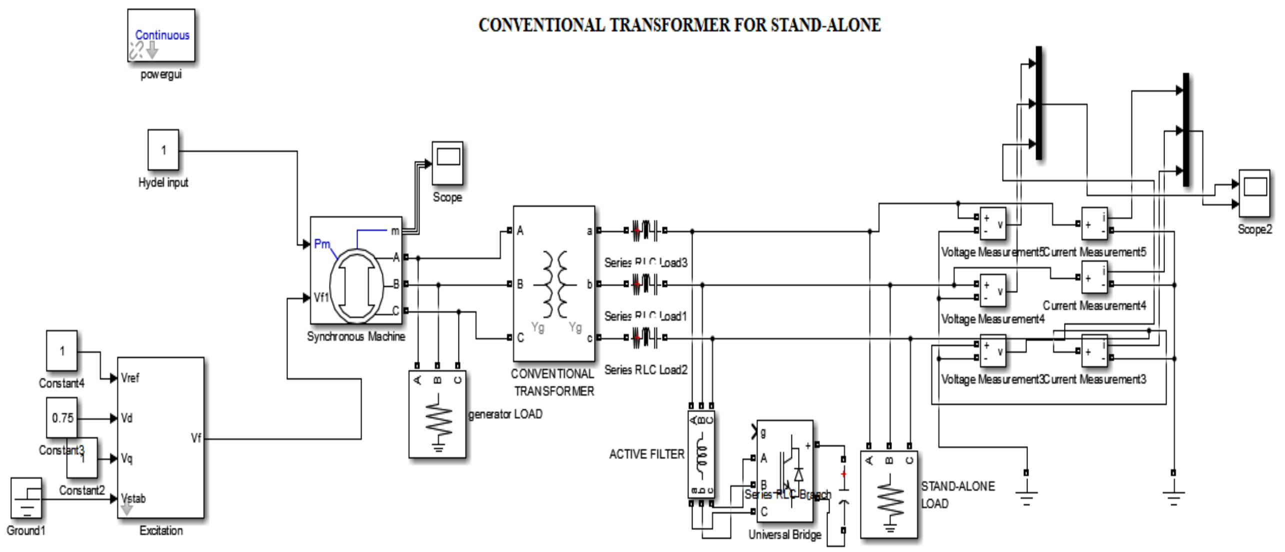


**Figure 3.** Simulink Block diagram of conventional transformer for stand-alone application

These are the main components of the conventional transformer structured to supply stand-alone load demand of about 10kw.

## C. Active Filters for Harmonics Mitigation

Harmonics forms the multiples of the fundamental frequency of the power system by non-linear loads, causing distortions in the current and voltage waveforms resulting in power quality issues such as voltage sags and swells. Due to these persisting problems caused by harmonics, power electronics such as active filters are mostly used to mitigate some of the harmonics present in the system. Active filters are made based on the band of frequencies allowance or rejection. Mostly in use are; low pass filter, high pass filter, band pass filter and band stop filter.

## 3. OPERATION AND CONTROL OF THE PROPOSED SMART TRANSFORMER

Smart Transformer is the key driver of this fast-growing smart grid system that delivers high-quality, effective and reliable power to meet the resentful dynamics of both AC and DC load demand and various system applications.

The main component structure of the Smart Transformer as shown in fig.4 consists of three-stage power converters, control and communication points. The first stage is the AC-DC rectifier, the second stage is the DC-DC chopper, and the third stage is the DC-AC converter (inverter) for stand-alone applications connected to the AC distribution lines. It also has control features from the dc-dc link point for the supply of special load DC voltage for military and hospital equipment within the locality.

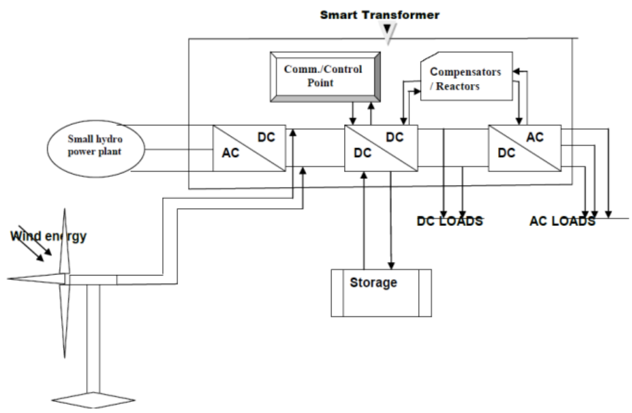


**Figure 4.** Block diagram of ST for stand-alone application

### A. Stand-alone Generation Station

Apart from the fact that ST uses AC sources such as small hydro-dams, it also contributes to the integration of DC distributed energies such as solar, wind, geothermal and tidal energy that can be used for stand-alone applications. Notwithstanding for the purpose of this proposed project, small hydro-dam and wind energy are utilized.

### B. ST for Power Distributions

With various special features of the smart transformer in addition to it conventional features, the ST is able to deliver about 85%-95% efficiency of the power generated. These special features are;

1. **AC to DC converter (Rectifier) section**: the AC to DC converting section is used to change the alternating current to direct current for easy control and manipulation.
2. **DC to DC converter (Chopper) section:** this section is used to step up and boost the converted DC voltage for high voltage application. In addition DC load demand can be supplied from this section.
3. **DC to AC converter (Inverter) section:** this section also is the point where high DC voltage is inverted to AC voltage for AC load applications.
4. **Communication and Control point:** is the section where the integration of Geospatial and Electric technology models, Information and communication technology (ICT) infrastructure, Controllers, field sensors, smart meters and distributed renewable generation and storage are controlled and manipulated for secured and quality distribution of both AC and DC power.

5. **Compensation/Reactors:** these devices are used to compensate any distortion of the voltage and current that may occur due switching effect of the power electronic devices or harmonics. in this proposed research work, the wind energy is controlled and operated as a main source of the compensation.

### C. Storage System

Energy storage system is the section where energy is stored for peak load hours. It also assists in the maintenance of any of the sourced power plants (hydro power plant or the wind mill), integration of EV infrastructure and for future development.

### 3.1 Load and frequency control of ST

Load and frequency control is a key factor in the stability of the voltage in the power system of which the transformer plays a key role. But since the ST uses the power electronics based device and phenomenon; frequency remains zero whiles the alternating current is converted into direct current for easy operation and control. Therefore in ST the main control point to satisfy load demand is the DC to DC boost converter though there would be a link control of the AC to DC converter (rectifier) and the DC to AC converter (inverter).

The simplified schematic diagram of the DC to DC boost converter for control of DC voltage to meet high DC voltage applications is illustrated in fig 5 above. For the design of the DC to DC boost converters, it is important to maintain the group of the above control mechanism; F (inv) = 1-F is used for reverse switching.

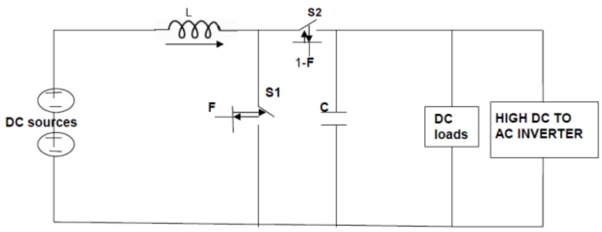


**Figure 5.** Simplified schematic diagram of DC to DC boost converter

Fig. 6 above illustrates the Matlab subsystem model of the proposed DC to DC boost converter where F = the function control for switching purposes (Hinov, 2018).

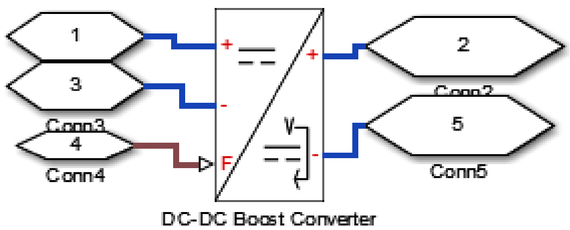


**Figure 6.** Subsystem Model of DC to DC Boost Converter

Mathematically;

$$L\frac{diL}{dt} = Vs - Finv.C \tag{4}$$

$$C\frac{dUC}{dt} = Finv.iL - \frac{UC}{R} \quad if\ iL\ \geq 0 \tag{5}$$

$$C\frac{dUC}{dt} = -\frac{UC}{R} \quad if\ iL = 0 \tag{6}$$

### 3.2 Voltage and Current Control of ST

Configuration control of voltage and current levels is very paramount in supplying power to meet various AC and DC load demands due to switching effect and other factor such as harmonics, change in load. Hence the DC tie line power from the converter end to the inverter end is configured below:

$$\Delta Ptie_{12},DC = (V_1\ E_1/X_{t1})\ Cos\ (\theta_1\text{-}\phi_1)\ (\Delta\theta_1\text{-}\ \Delta\phi_1) \qquad (7)$$

Therefore; $\Delta Ptie_{12}$, DC = $P_{12}$, DC $(\Delta\theta_1\text{-}\ \Delta\phi_1)$,

Where $P_{12}$, DC = $(V_1\ E_1/X_{t1})\ Cos\ (\theta_1\text{-}\phi_1)$ shows the synchronizing factor of the converter end.

$$\Delta Ptie_{21},\ DC = (V_2\ E_2/X_{t2})\ Cos\ (\theta_2\text{-}\phi_2)\ (\Delta\theta_2\text{-}\ \Delta\phi_2) \qquad (8)$$

Sending power from HVDC inverter;

$\Delta Ptie_{21}$, DC = $P_{21}$, DC $(\Delta\theta_2\text{-}\ \Delta\phi_2)$,

Where $P_{21}$, DC = $(V_2\ E_2/X_{t2})\ Cos\ (\theta_2\text{-}\phi_2)$ also shows the synchronizing factor of the inverter end (Khanjanzadah et al., 2020).

Using the same load parameters, CT parameters from table 2 and table 3 respectively; fig.7 clearly illustrates the Simulink model of the proposed smart transformer with 180 mode inverter control and configuration. The parameters for the wind turbine and the DC machine are shown in table 4 and table 5 respectively. The filter shown in fig.7 on-like what is shown in the CT model in fig. 3 is wind sourced and hence there is no need for any external source. In addition, for a better operation and control of this proposed project, storage system in form of a capacitor shown in the diagram are installed resulting in the negligibility of disturbances in the system as illustrated in fig. 9 of simulated results. MOSFETs are used as power electronic device for the configurations because of its reasonable efficiency for high frequency application.

**Table 4.** Parameters for Wind Turbine Configuration

| Parameters | Values |
|---|---|
| Nominal mechanical output power (W) | 200W |
| Base power of the electrical generator (VA) | 200/0.9VA |
| Base wind speed (m/s) | 12m/s |
| Maximum power at base wind speed (pu) of nominal mechanical power | 0.73pu |

**Table 5.** Parameters for Dc Machine

| Parameters | Values |
|---|---|
| Armature resistance and inductance [Ra (ohms) La (H) ] | [0.6569 0.008734] |
| Field resistance and inductance [Rf (ohms) Lf (H) ] | [92.78 16.23] |
| Field-armature mutual inductance Laf (H) | [0.7688] |
| Total inertia J (kg.m^2) | [0.1646] |
| Viscous friction coefficient Bm (N.m.s) | [0.006126] |
| Coulomb friction torque Tf (N.m) | [4.223] |
| Initial speed (rad/s) | [1] |

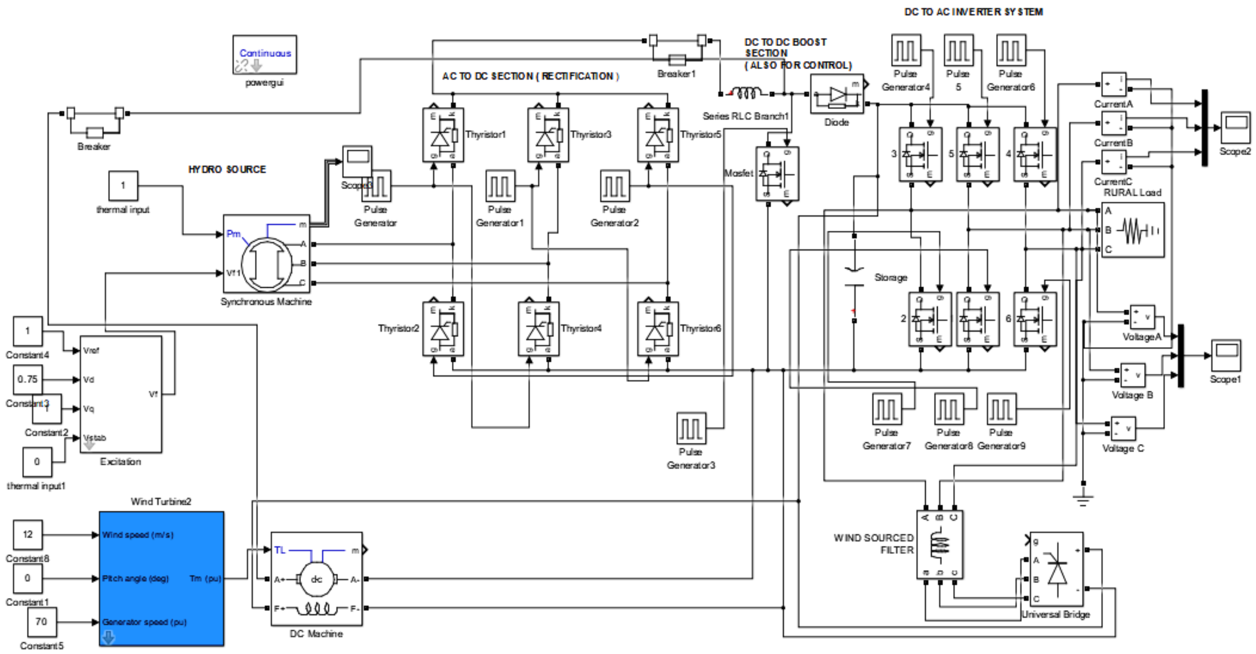


**Figure7.** Simulink Block diagram model of smart transformer for stand-alone application

## 4. SIMULATION OUTPUT RESULTS

### 4.1. Load and Frequency Control

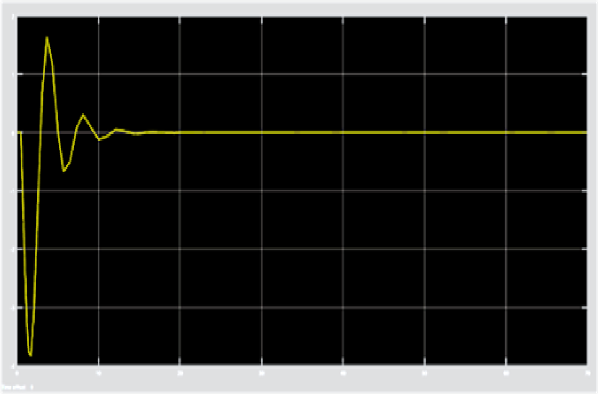

**Figure 8.** Load and frequency control of CT

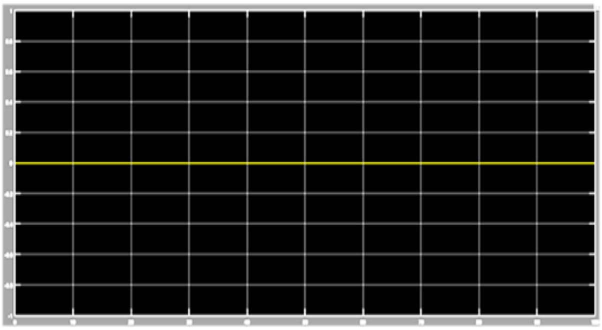

**Figure 9.** Smart control of ST

### 4.2. Current and Voltage control Simulation

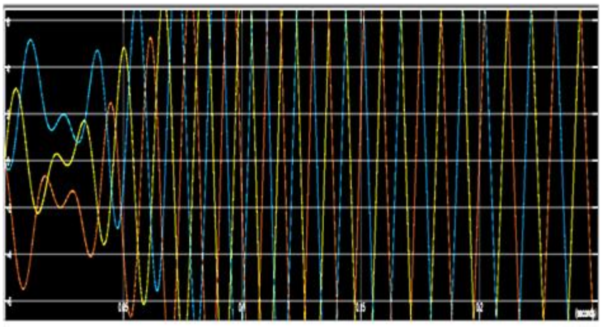

**Figure 10.** CT Current with no filter

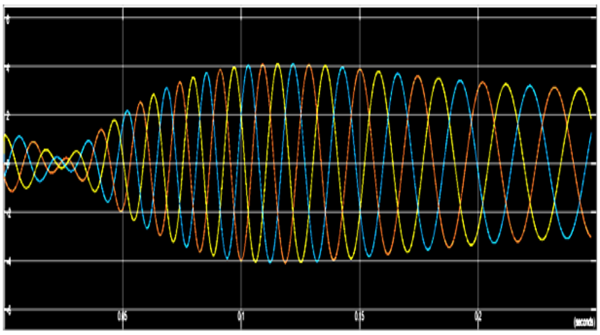

**Figure 11.** CT Current with filter

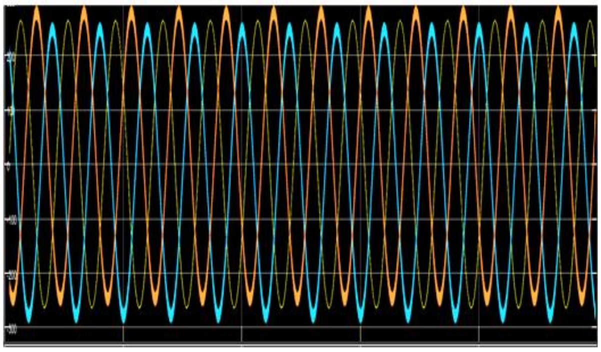

**Figure 12.** CT Voltage without filter

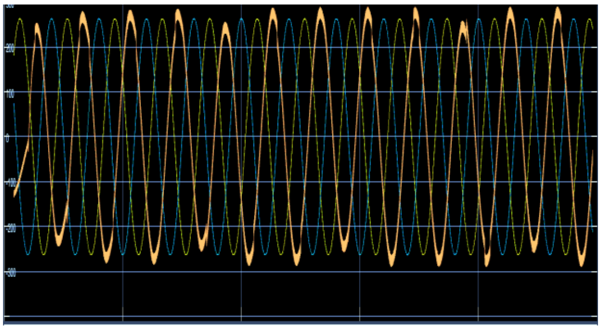

**Figure 13.** CT Voltage with filter

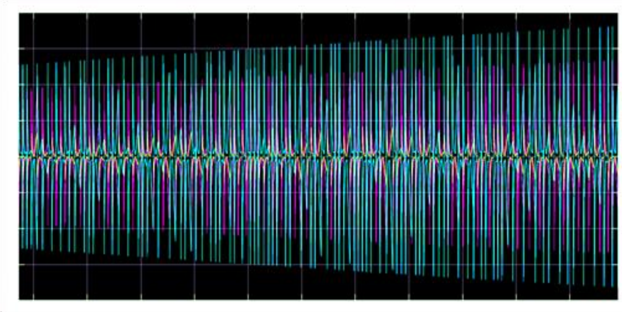

**Figure 14.** ST 180 Mode Inverter Current without wind sourced filter

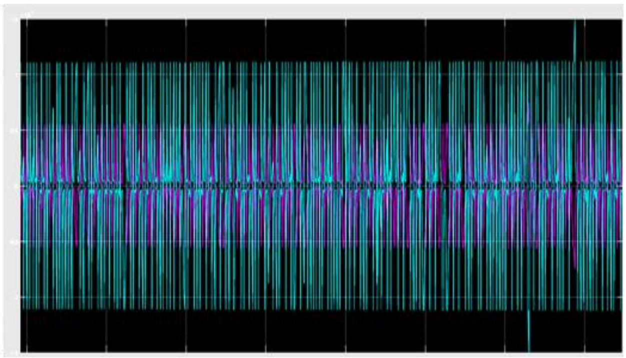

**Figure 15.** ST 180 Mode Inverter Current with wind sourced filter

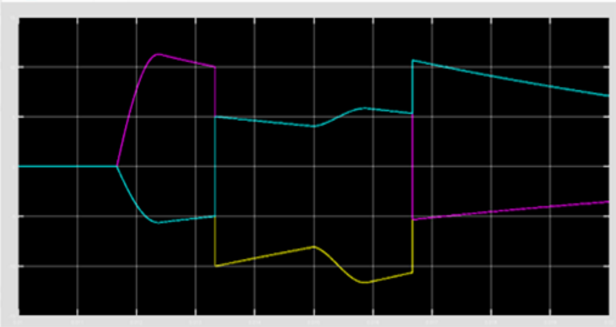

**Figure 16.** ST 180 Mode Inverter Voltage without wind sourced filter

## 5. SIMULATION ANALYSIS

The simulations above clearly depict the output results of both the conventional and smart transformer in its load, frequency, current and voltage (power) operational control modes supplying about 10kW, 50HZ to both AC and DC load demands in the rural or remote area. At sampling frequency of 0.01kHZ, setoff time of zero and 0.1s sampling time, its took the conventional transformer about 16s to attain total system stability compared to the smart transformer whose smart features always help to achieve very fast total system stability of about 0.44ms which is significantly zero under load and frequency control as shown fig. 8 and fig. 9 respectively.

The simulation results shown in fig. 10 and fig. 14 illustrate the impact of current waveform distortion of both CT and ST with the operation of only design features of the transformer without filters; at sampling time (t) of T = 0.248s, it was observed that the current signal of each phase was distorted and could not reach it peak level and hence limited current flow through the system for a period of about 0.1s before the transformer could adjust as shown in fig. 10. ST in fig. 14 showed similar result with no distortion in waveform but adjusted to the current peak level at $7x10^{-5}$s. Fig. 11 showed no distortion in the currents waveform of the CT as a result of the filter connected to the system but was able to adjust to the peak level at relatively very slow time of about 0.058s whiles the ST maintained it standard peak level since it was connect with the smart wind sourced filter as shown in fig. 15.

Figures 12 and 16 also show the simulation result of CT and ST voltages without any compensator; fig. 12 of the CT showed a lot of harmonic components present in the system whiles ST in fig. 16 shows voltage dip and was able to adjust the voltage level within approximately 0.012s with controlled harmonic component based on its smart features of wind integration. Fig. 13 shows CT with relatively less harmonic component in the system as a result of the filter as compensator connect to it, though it is less but can high enough to cause low or high frequency level of the fundamental frequency which is 50HZ. Due to the 180 mode configuration and control of wind sourced filter of the ST as shown in fig. 18, compensation of each line voltages are done expeditiously resulting in effective disturbance control hence harmonics or any form of disturbances do not affect the voltage waveform levels of the system.

## 6. CONCLUSION

Based on the simulation analysis and other salient points discussed in this research paper, a conclusion can be drawn on the benefits of smart transformer over conventional transformer for stand-alone operations;

- Greener energy and sustainable system implementation
- Quality and reliable distribution voltage profile
- System stability due to the smart features for operations and control
- Relatively less system operation cost due to the integration of distributed energies
- Effective disturbance control as various storage devices, sensors, ICT infrastructures are implemented.

Though initial cost of installation maybe expensive due to the smart infrastructures, researchers and system engineers could design futuristic models and designs to reduce such cost. Notwithstanding, the proposed research design was effectively operated and controlled using the R2015a Matlab software for stand-alone applications.

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**Author Contributions**

The paper conceptualization, methodology, software, validation, formal analysis, investigation, resources, data collections, original draft writing preparation, visualization, has been done by Mr. Bismark Budu (1st author). The supervision, editing, review writing and administration of the project, has been done by Professor Bhagwan Shree Ram (2nd author).

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