A Concept 'Smart Switch' for Single-Phase Transformer and Reactor Control

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Abstract—Introduced to electrical power networks at the turn of the century, the use of power electronic devices to control and regulate single-phase networks has trailed behind. A likely reason for this outcome is the relative cost of 'smart devices' in a system of low earned revenue.

Now a feature of grid modernisation projects, interest in 'smart devices' as a means to extend the useful life of distribution assets, delay capital expenditure, lower operating costs and to improve the supply reliability, is growing.

Described in this paper for the control of single-phase transformers and reactors is a concept 'smart switch' that uses a low voltage low power thyristor. Built with a novel magnetic core and winding arrangement, the disconnection and reconnection of a transformer or reactor is controlled by the semiconductor switch. The concept design is demonstrated in this paper for a thermal overload and switched shunt reactor transformer applications.

Index Terms—Power electronics, single-phase distribution transformers and reactors, the smart grid concept, SWER line voltage regulation, thermal overload relay protection, illegal electricity connection.

I. INTRODUCTION

To release additional line capacity as the demand for power increases, fixed shunt reactors, which are used to mitigate the Ferranti effect in Single Wire Earth Return Systems (SWER), must be disconnected. In a low cost design of low earned revenue however, the expense of a high voltage automated switch for this purpose is unreasonable. An automation barrier, shunt load reactors of lower voltage and rating are instead connected at points of low voltage supply where they can be switched economically [1].

Illegal electricity connections and meter tampering usually in low voltage networks is a worldwide problem that deprives utilities of revenue. A safety hazard, the consequence of the illegal practice is poor supply quality and damage to equipment [2] as an overload will usually result in a supply trip or the failure of equipment if not detected. Remote from a service depot, an interruption in supply because of an overload condition can be prolonged.

Presented in this paper a concept 'smart switch' for single-phase transformers offers an economic solution to the problem of fixed shunt reactors, area wide supply trips because of an overload condition and thermal damage to equipment.

Equipped with a voltage or overload sensor, a smart transformer or reactor is with power electronic technology [3], [4] able to regulate and control the voltage and power in a single-phase distribution network autonomously.

I. AUTONOMOUS SMART DEVICE

A smart device in autonomous electricity grid architecture is with the latest sensor technologies largely able to control itself [5]. Equipped with a communication link, the smart switch device proposed in this paper equates to:

- A load management tool for single-phase distribution networks.
- A voltage management tool for single-phase distribution networks.
- A power quality management tool for single-phase distribution networks.

II. CONCEPT SWITCH

In Figure 1 (a), (b) and (c), the interaction between windings $W_2$, $W_3$ and $W_4$, for a voltage applied to winding $W_1$, is a function of the magnetic core fluxes $\phi_1$, $\phi_2$ and $\phi_3$, which for current to flow in the windings must be in balance [6]-[8].

A product of the winding current $I_{W2}$, $I_{W3}$ and $I_{W4}$, for a voltage applied to winding $W_1$, is a function of the magnetic core fluxes $\phi_1$, $\phi_2$ and $\phi_3$, which for current to flow in the windings must be in balance [6]-[8].

Fig. 1. A transformer core design with three separate magnetic circuits and a common winding $W_1$.

A product of the winding current $I_{W2}$, $I_{W3}$, $I_{W4}$ and connected load impedance $Z_{L2}$, $Z_{L3}$ and $Z_{L4}$, Figure 2, the voltage drop – $(I_{W2}Z_{L2} + I_{W3}Z_{L3} + I_{W4}Z_{L4})$ is equal to the terminal voltage $V_{Wn}$.

The terminal voltage $V_{Wn}$ is $V_{Wn} = E_{Wn} - (I_{Wn}R_{Wn} + jI_{Wn}X_{Wn})$. 

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where \( E_{Wn} \) is the induced winding voltage, \( R_{Wn} \) the winding resistance and \( X_{Wn} \) the winding leakage reactance.

Across each winding, the voltage drop \(-I_{Wn}R_{Wn}\) is \(0.3V_{Wn}\) for a load impedance \(Z_{L2} = Z_{L3} = Z_{L4}\) and winding turns \(N_{W2} = N_{W3} = N_{W4}\).

The load impedance \(Z_{L2}\) with winding \(W_2\) open circuit, Figure 4(b), is \(Z_{L2} = \infty \Omega\) . The winding current \(I_{W2}\), \(I_{W3}\) and \(I_{W4}\) are for this condition \(I_{W2} = I_{W3} = I_{W4} = 0\), which satisfies the condition of magnetic balance for an open circuit winding, e.g. the core flux \(\phi_2 = \phi_3 = \phi_4 = 0\).

Winding \(W_2\) is in Figure 4(c) short circuit, and for this condition the terminal voltage \(V_{W1}\) and winding current \(I_{W1}\) are zero because the voltage drop across winding \(W_3\) and \(W_4\) is \(0.5V_{Wn}\) for a load impedance \(Z_{L3} = Z_{L4}\).

The volt per turn is for turns \(N_{W1} = N_{W2} = N_{W3} = N_{W4}\):

\[
\frac{E_{W1}}{N_{W1}} = \frac{E_{W2}}{N_{W2}} = \frac{E_{W3}}{N_{W3}} = \frac{E_{W4}}{N_{W4}} \quad (1)
\]

The ampere-turn relationship for magnetic balance is:

\[
I_{W1}N_{W1} = I_{W2}N_{W2} = I_{W3}N_{W3} + I_{W4}N_{W4} \quad (2)
\]

The winding current \(I_{W1}\) is for a voltage \(V_{W1}\):

\[
I_{W1} = I_{W2} + I_{W3} + I_{W4} \quad (3)
\]

The load impedance \(Z_{L1}\) is in Figure 5 referred to winding \(W_1\).

The referred load impedance \(Z_{L1}'\) is:

\[
Z_{L1}' = Z_{L4}(V_{W1}/V_{Wn})^2 = V_{W1}/I_{W1} \quad (4)
\]

Figure 7 is a test model of the transformer described.
Wound around the inner limbs of three single-phase magnetic circuits are two windings \( W_{11} \) and \( W_{22} \). The windings have an equal number of turns. Wound over the outer limbs are windings \( W_3 \), \( W_4 \), and \( W_5 \), which also have the same number of turns. The turn ratio between the inner and outer limb windings is 0.5:1. The three magnetic circuits, which are shown, mutually displaced by 120°, have no effect on the transformer action. A different design arrangement is possible.

Fig. 8. The schematic arrangement of a transformer test model with three separate magnetic circuits and windings wound around the inner and outer limbs.

In Figure 9(a) a 220 V single-phase voltage is connected across winding \( W_{11} \). The results for a resistive load connected across windings \( W_{12}, W_3 \) and \( W_4 \), with winding \( W_2 \) open circuit, are shown.

Fig. 9(a). The test results of a 220 V single-phase voltage applied across \( W_{11} \) with \( W_2 \) open circuit and a resistive load connected across windings \( W_{12}, W_3 \) and \( W_4 \).

The test results for a resistive load connected across winding \( W_3 \) and \( W_4 \), with winding \( W_2 \) short circuit and winding \( W_{11} \) open circuit are shown in Figure 9(b). The circuit has a 220 V single-phase voltage source connected across winding \( W_{12} \).

Fig. 9(b). The test results of a resistive load connected across windings \( W_3 \) and \( W_4 \) and \( W_5 \), with winding \( W_{11} \) open circuit, are shown.

The test results for a resistive load connected across winding \( W_2 \), \( W_3 \) and \( W_4 \), with winding \( W_{11} \) open circuit are shown in Figure 9(c).

Fig. 9(c). The test results of a 220 V single-phase voltage applied across \( W_{12} \) with \( W_{11} \) open circuit and a resistive load connected across windings \( W_2, W_3 \) and \( W_4 \).

The results obtained in Fig 9(a) and Fig. 9(b) confirm the hypothesis of a concept: a switch previously described. Connected across winding \( W_2 \) a solid state switch of low voltage and low power can be used to control the current in windings \( W_3 \) and \( W_4 \), and by association the current in winding \( W_{11} \). The results also demonstrate the load dependent distribution of voltage across each transformer winding.

II. SHUNT REACTOR TRANSFORMER CASE
The core and winding arrangement of a novel shunt reactor transformer design for SWER line voltage regulation is shown in Figure 10.

![Diagram of core and winding arrangement](image1)

**Fig. 10.** The core and winding arrangement of a single-phase shunt reactor transformer for SWER line voltage control

Similar in construction to the test model Fig. 8, the transformer reactor for line voltage control has tertiary windings T<sub>1</sub>, T<sub>2</sub> and T<sub>3</sub> on the outer limbs and a primary P and Secondary S winding wound around the inner limbs. Connected to the tertiary windings are (shunt) load reactors L<sub>11</sub>, L<sub>12</sub> and L<sub>13</sub>, Figure 11.

![Diagram of single-phase switched shunt reactor transformer schematic](image2)

**Fig. 11.** A single-phase switched shunt reactor transformer schematic for SWER line voltage control

The primary winding, which is grounded, is connected to a high voltage line. An intelligent electronic device (IED), which is connected to the secondary winding, controls the flow of an inductive current in the primary winding by way of a voltage sensor, inductors L<sub>12</sub>, L<sub>13</sub> and L<sub>13</sub> and a solid state switch SW<sub>1</sub>. Switch SW<sub>2</sub> is an option for a stepped voltage adjustment. The tertiary winding current T<sub>n</sub> is zero when switch SW<sub>1</sub> conducts, e.g. I<sub>T1</sub> = I<sub>T2</sub> = I<sub>T3</sub> = 0 Figure 12(a). Rated for a highly inductive load, the power rating of switch SW<sub>1</sub> is low as the voltage drop across the load inductors L<sub>12</sub> and L<sub>13</sub> is equal to the induced voltage. Switch SW<sub>1</sub> has a blocking voltage equal to or greater than the highest anticipated open circuit winding voltage, which in Figure 12(b) is 800 V. Built for an inductive rating of 25 kVAr, the reactor transformer has with switch SW<sub>2</sub> and inductor L<sub>11</sub> a stepped rating of 25 kVAr and 16 kVAr, Figure 12(c). Switch SW<sub>2</sub> is rated for the load current of the (shunt) load inductor L<sub>11</sub> and open circuit voltage of tertiary winding T.<sub>n</sub>

![Equivalent circuit diagram](image3)

**Fig. 12.** The equivalent circuit Fig. 11 (a) when switch SW<sub>1</sub> conducts, (b) when switch SW<sub>1</sub> is not conducting and (c) when SW<sub>2</sub> conducts but SW<sub>1</sub> does not conduct. The winding resistance and leakage reactance is not shown.

The shunt reactor transformer design has with off-the-shelf 400 V 41 mH (shunt) load reactors the same rating as a fixed shunt reactor, which is 25 kVAr [9]. The tertiary windings are sized for the connected load. The state of the solid state bi-directional triode thyristor (TRIAC) switches is controlled by a voltage sensor with hysteresis and time delay settings. Because the revenue earned from energy retailing has with the introduction of battery storage and solar PV technologies declined steadily power electronic devices are today viewed as a viable upgrade path to release network capacity, [10]-[17].

Discussed in this paper, is a battery energy storage system (BESS) that may be integrated in the shunt reactor transformer design Fig 11 as an energy storage solution to release additional line capacity.

### A. Line voltage regulation case studies

Invented in New Zealand in 1925, the Single Wire Earth Return (SWER) distribution system is widely used to supply rural loads of low load density. Connected between a single conductor and ground, the load current of a single-phase transformer in a SWER system flows back to the ground terminal of an isolating transformer, Figure 13, or the ground terminal of a three-phase supply [18]. Although a cost effective supply solution, SWER designs often have a poor
voltage regulation and suffer from high losses and capacity constraints because of a high line charging current and high line impedance.

Fig. 13. A single line SWER distribution system that is constructed with an isolating transformer

The phase voltage of a 33 kV distribution system is 19.1 kV or 12.7 kV for a 22 kV system or 6.7 kV for an 11 kV system.

A load flow model of a SWER distribution line [19], [20] that is supplied from two phases of a three-phase 33 kV distribution line is shown in Figure 14. Included in the model is a 33/19.1 kV 150 kVA isolating transformer and two line sections, L1 and L2.

Fig. 14. A medium length SWER distribution line supplied from a 150 KVA 33/19.1 kV isolating transformer.

The branch currents in this model are:

\[ I_s = I_1 + I_2 \]  
(12)

\[ I_2 = I_3 + I_r \]  
(13)

\[ I_r = I_s - I_3 \]  
(14)

\[ I_5 = I_6 + I_r \]  
(15)

By substitution \( I_s \) is:

\[ I_s = I_1 + I_2 + I_4 + I_6 + I_r \]  
(16)

and rewritten \( I_s \) is:

\[ I_s = (y/2)V_s + (y/2)V_r + I_r \]  
(17)

Considering a homogeneous line where \( L = L1 + L2 \), then the current \( I_s \) is:

\[ I_s = (Y/2)V_s + (Y/2)V_r + I_r \]  
(18)

The node voltage \( V_s \) is by substitution:

\[ V_s = V_r + I_s Z_L = V_r + ((Y/2)V_s + (Y/2)V_r + I_r)Z_L \]  
(19)

At no load, the node voltage \( V_s \) is \( V_s = (I + (Z_L Y/2)) V_r \) and the voltage drop across line L is:

\[ V_s - V_r = ((Z_L Y/2)) V_r \]  
(20)

Neglecting the line resistance, the voltage drop by substitution is:

\[ V_s - V_r = jX_c x \frac{1}{2} \]  
(21)

For a negative sign, the receiving voltage \( V_r \) is greater than the sending voltage \( V_s \).

The study case parameters of a typical medium length SWER distribution line Fig. 14 are listed in Table 1, Table 2 and Table 3.

Table 1

| Base Values Fig. 14 |
|---------------------|
| \( V_{base} \) | – | 19.1 kV |
| \( S_{base} \) | – | 150 kVA |
| \( I_{base} \) | 150 kVA / 19.1 kV | 7.85 Amps |
| \( Z_{base} \) | (19.1 kV)/ 150 kVA | 2432 Ohms |
| \( Y_{base} \) | 1/2432 Ohms | 0.4112 mS |

Table 2

| Branch Values Fig.14 |
|----------------------|
| \( R_{pu} \) | \( X_{pu} \) | \( Y/2 pu \) |
| Ground R | 0.0004 | – | – |
| Isol. Trfr. R | 0.015 | 0.03 | – |
| Line 11 Z | 0.10 | j0.04 | 0.304 |
| Line 12 Z | 0.10 | j0.04 | 0.304 |

Table 3

| Shunt Reactor, Battery Storage and Load Values Fig. 14 |
|------------------------------------------------------|
| \( P_{pu} \) | \( Q_{pu} \) | pf |
| Shunt Reactor | 0.0 | 0.17 | – |
| Battery Storage | 0.18 | – | +0.9 |
| Load | 0.20 | 0.12 | 0.85 |

Seen in Table 2, the use of high tensile light weight stranded Steel Core Galvanised Zinc (SC/GZ) or stranded Steel Core...
Aluminium Clad (SC/AC) conductors to increase the span distance results in a high line a.c. resistance. Using a MATHCAD software program, the node voltages and branch currents are determined from a Backward/Forward load flow sweep method [21, 22]; where the node voltages, in an initial backward walk from node A2 to A1, are kept the same before they are then adjusted in a forward walk keeping the branch currents the same for recursive iterations.

1) Case study 1 – Line charging current

At no-load the receiving end voltage $V_{r2}$ is higher than the sending end voltage $V_{s1}$ Table 4. Across line L1 and L2, the voltage drop for a source voltage $V_T = 1.0$, is $V_{s1} - V_{r2} = - (0.03 + j0.14)$. Given a contract voltage of +5% of nominal voltage $V_s$, the customer supply transformers at nodes $V_{r1}$, $V_{s2}$ and $V_{r2}$ must be set on a minus voltage tap to stay within limit.

| $V_T$ | $V_{s1}$ | $V_{r1}$ | $V_{s2}$ | $V_{r2}$ |
|-------|-----------|-----------|-----------|-----------|
| 1.0   | 1.04–j0.02| 1.06–j0.12| 1.06–j0.12| 1.07–j0.16|

The line charging current is in Table 5 higher at the sending end than at the receiving end.

| $I_{s1}$ | $I_1$ | $I_2$ | $I_{r1} = I_{s2}$ | $I_{r2} = I_{s1}$ |
|----------|-------|-------|-------------------|-------------------|
| 0.11     | +j0.30| 0.00  | 0.11              | 0.08              |
|          |       | 0.08  | +j0.98            | +j0.66            |
|          |       |       | -j0.33            | -j0.33            |
|          |       |       | 0.03              | 0.04              |

For a fully loaded three-phase system where the source voltage $V_T = 0.9V_s$, the supply transformers must now be set on a plus voltage tap to stay within limit.

| $V_T$ | $V_{s1}$ | $V_{r1}$ | $V_{s2}$ | $V_{r2}$ |
|-------|-----------|-----------|-----------|-----------|
| 0.9   | 0.93–j0.02| 0.96–j0.11| 0.96–j0.11| 0.97–j0.14|

The line charging current Table 7 is now lower than in Table 5 for an un-loaded three-phase system.

2) Case study 2 – Shunt reactors at no load

With 25 kVAr shunt reactors installed at nodes $V_{r1}$, $V_{s2}$ and $V_{r2}$, the SWER line has a flat voltage profile when the three-phase system is at no-load. Set on a plus voltage tap, a voltage drop when the line is loaded is allowed for at points of customer supply.

| $V_T$ | $V_{s1}$ | $V_{r1}$ | $V_{s2}$ | $V_{r2}$ |
|-------|-----------|-----------|-----------|-----------|
| 1.0   | 1.02–j0.01| 1.03–j0.06| 1.03–j0.06| 1.04–j0.08|

The branch currents $I_2$ and $I_4$ are with shunt lower Table 9.

| $I_{s1}$ | $I_1$ | $I_2$ | $I_{r1} = I_{s2}$ | $I_{r2} = I_{s1}$ |
|----------|-------|-------|-------------------|-------------------|
| 0.08     | 0.00  | 0.08  | 0.05              | 0.02              |
|          | +j0.31| +j0.47| +j0.31            | +j0.16            |
|          |       |       | +j0.16            | +j0.16            |

3) Case study 3 – Load demand and line capacity

With the customer supply transformers on a maximum +5% voltage tap at nodes $V_{r1}$, $V_{s2}$ and $V_{r2}$ the supply voltage is below the acceptable limit when both the three-phase and single-phase networks are fully loaded Table 10.

| $V_T$ | $V_{s1}$ | $V_{r1}$ | $V_{s2}$ | $V_{r2}$ |
|-------|-----------|-----------|-----------|-----------|
| 0.9   | 0.9       | 0.85      | 0.85      | 0.84      |
|       | -j0.02    | -j0.05    | -j0.05    | -j0.06    |

4) Case study 4 – Battery Energy Storage System

Released at high load demand, the energy stored in a battery energy storage system (BESS), Figure 15, provides additional line capacity to support the line voltage Table 12. The current $I_4$ at peak-load, Table 13, is with a 24 kW BESS at node $V_{r1}$ and $V_{r3}$, Fig. 14, lower than the line current $I_4$ Table 11. The voltage drop across line L1 and L2 is with both BESSs in service lower.

The battery bank may be charged from the power grid at a leading power factor in times of light load or from a solar charging system when the irradiance for this purpose is sufficient. With the batteries fully charged, excess capacity is then available to be exported to the power grid.

A leading power factor setting is appropriate for the export of power to the power grid because with a unity power factor setting the imaginary voltage drop remains the same.
Table 12

Node voltages (Fig. 14.)
Supply side peak load shaving for a 27 kVA ESS at node \( V_r_1 \) and \( V_r_2 \)

| \( V_T \) | \( V_{A2} \) = \( V_s_1 \) | \( V_r_1 \) | \( V_{r2} \) | \( V_{r3} \) |
|---|---|---|---|---|
| 0.9 | 0.91 | 0.91 | 0.91 | 0.92 |
| \(-j0.02\) | \(-j0.08\) | \(-j0.08\) | \(-j0.04\) |

Table 13

Branch currents (Fig. 14.)
Supply side peak load shaving for 27 kVA ESS at node \( V_r_1 \) and \( V_r_2 \)

| \( I_s_1 \) | \( I_1 \) | \( I_2 \) | \( I_3 \) | \( I_{r1} - I_{s2} \) | \( I_{r4} \) | \( I_5 \) | \( I_6 \) |
|---|---|---|---|---|---|---|---|
| 0.41 | 0.19 | 0.21 | 0.02 | 0.20 | 0.17 | 0.03 |
| \(+j0.59\) | \(+j0.12\) | \(+j0.46\) | \(+j0.19\) | \(+j0.28\) | \(+j0.07\) | \(+j0.21\) |

III. THERMAL OVERLOAD CASE

Over temperature, accelerated aging and the risk of transformer failure, can have an adverse effect on the operation of an electricity power grid. Rated for a maximum temperature rise above ambient temperature, the insulation-life of a transformer is shortened by an operating temperature above the design limit. In Figure 16, either the top oil or hot-spot temperature measurement functions to protect the transformer against an overload by opening switch \( SW_1 \). Switch \( SW_1 \) operates autonomously to isolate an overload before the load is restored after an appropriate cooling period. An 'Adaptive Transformer Thermal Overload' protection scheme, which measures the ambient temperature, has only one setting – a per unit loss-of-life factor.

Equipped with a communication link in a Supervisory Control and Data Acquisition (SCADA) system, an operator is informed of an overload when it occurs. The switch may also in this system be used to redistribute single-phase loads and to establish a balance between the supply and demand for energy. It is also a tool to dissuade illegal connections.

While numeric thermal overload relays typically use a combination of current, ambient temperature and transformer top oil temperature to detect the presence of an over-load, the operating temperature of a transformer can also be estimated by a thermal-replica model. In this model a maximum temperature rise is calculated from a measured current. A simple representation of the operating temperature of a transformer, the model does not account for variations in the ambient temperature and is not a true top-oil or winding or hot-spot temperature measurement [23].

IV. CONCLUSION

A low voltage, low power bipolar solid state switch for single-phase transformer and reactor control was presented in this paper. Central in the switch concept design is a novel magnetic core and winding arrangement, which was demonstrated for an autonomous SWER line shunt reactor application and a 'smart' single-phase transformer overload protection and control system.

The concept switch deals with the unacceptable high cost of a high voltage switch, which is needed in SWER distribution networks for line shunt reactors to release additional line capacity as the demand for power grows.

As an intelligent control switch it also addresses the need for an autonomous overload protection scheme to protect single-phase transformers against overloads, dissuade illegal electricity connections, and to re-distribute or balance load with supply.

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