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 ϕ_1 , ϕ_2 and ϕ_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.

Fig. 4(a). The equivalent circuit of a load Z_{Ln} across each winding W_n (b) when one winding is short circuit, and (c) when one winding is open circuit. The winding resistance R_{Wn} and leakage reactance X_{Wn} is not included.

Across each winding, the voltage drop $-I_{Wn}$ 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} is 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 $\phi_1 = \phi_2 = \phi_3 = 0$.

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 $N_{W1} = N_{W2} = N_{W3} = N_{W4}$:

$$E_{W1}/N_{W1} = E_{W2}/N_{W2} = E_{W3}/N_{W3} = E_{W4}/N_{W4} \quad (1)$$

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_{Ln} is in Figure 5 referred to winding W_1 .

Fig. 5. The equivalent circuit of a referred load impedance Z_{Ln}' with a voltage V_{W1} applied across winding W_1 .

The referred load impedance Z_{Ln}' is:

$$Z_{Ln}' = Z_{Ln} (V_{W1} / V_{Wn})^2 = V_{W1} / I_{W1} \quad (4)$$

Shown in Figure 6(a), (b) and (c), for an alternating voltage V applied across W_1 , current circulates in winding W_3 and W_4 if the solid state switch S_1 conducts (the switch is closed). The flow of current ceases when switch S_1 is open (the solid state switch does not conduct).

Fig. 6. The core flux for (a) a conducting solid state switch S_1 across winding W_2 , and (b) a load impedance Z_{L3} across winding W_3 , and (c) a load impedance Z_{L4} across winding W_4 with a voltage V applied across windings W_1 .

A. Transformer simulation test

In Figure 7 is a test model of the transformer described.

Fig. 7. The magnetic circuit and winding arrangement of a transformer test model used in the design of a low voltage low power single-phase concept switch

Wound around the inner limbs of three single-phase magnetic circuits are two windings W_{11} and W_{22} Figure 8. The windings have an equal number of turns. Wound over the outer limbs are windings W_2 , W_3 and W_4 , 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 winding 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 winding 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 with winding W_2 short circuit and a 220 V single-phase voltage applied across W_{12}

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 winding 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.

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_1 , T_2 and T_3 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_{11} , L_{12} and L_{13} , Figure 11.

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_{11} , L_{12} and L_{13} and a solid state switch SW_1 . Switch SW_2 is an option for a stepped voltage adjustment. The tertiary winding current T_n is zero when switch SW_1 conducts, e.g. $I_{T1} = I_{T2} = I_{T3} = 0$ Figure 12(a). Rated for a highly inductive load, the power rating of switch SW_1 is low as the voltage drop across the load inductors L_{12} and L_{13} is equal to the induced voltage. Switch SW_1 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_2 and inductor L_{11} a stepped rating of 25 KVAR and 16 KVAR, Figure 12(c). Switch SW_2 is rated for the load current of the (shunt) load inductor L_{11} and open circuit voltage of tertiary winding T_1 .

Fig. 12. The equivalent circuit Fig. 11 (a) when switch SW_1 conducts, (b) when switch SW_1 is not conducting and (c) when SW_2 conducts but SW_1 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:

$$I_{S1} = I_1 + I_2 \quad (12)$$

$$I_2 = I_3 + I_{r1} \quad (13)$$

$$I_{r1} = I_{S2} = I_4 + I_5 \quad (14)$$

$$I_5 = I_6 + I_{r2} \quad (15)$$

By substitution I_{S1} is:

$$I_{S1} = I_1 + I_3 + I_4 + I_6 + I_{r2} \quad (16)$$

and rewritten I_{S1} is:

$$I_{S1} = (y/2)V_{S1} + (y/2)V_{r1} + (y/2)V_{S2} + (y/2)V_{r2} + 0 \quad (17)$$

Considering a homogeneous line L where $L = L1 + L2$, then the current I_S is:

$$I_S = (Y/2)V_S + (Y/2)V_r + I_r \quad (18)$$

The node voltage V_S is by substitution:

$$\begin{aligned} V_S &= V_r + I_S \cdot Z_L = V_r + ((Y/2)V_S + (Y/2)V_r + I_r)Z_L \\ &= (1 + (Z_L \cdot Y/2)) V_r + Z_L I_r \end{aligned} \quad (19)$$

At no load, the node voltage V_S is $V_S = (1 + (Z_L \cdot Y/2)) V_r$ and the voltage drop across line L is:

$$V_S - V_r = ((Z_L \cdot Y/2)) V_r \quad (20)$$

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

$$\begin{aligned} V_S - V_r &= jX_L \times \frac{1}{2}(jX_C) V_r \\ &= -\frac{1}{2}(X_L \cdot X_C) V_r \end{aligned} \quad (21)$$

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}	$(19.1 \text{ kV})^2 / 150 \text{ kVA}$	2432 Ohms
Y_{base}	$1 / 2432 \text{ Ohms}$	0.4112 mS

Table 2
Branch Values Fig. 14

	R pu	X pu	Y/2 pu
Ground R	0.0004	—	—
Isol. Trfr. Z	0.015	0.03	—
Line l1 Z	0.10	j0.04	0.304
Line l2 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_{L2} to A1_T, 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_n , 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.

Table 4
No-load node voltages $V_T = 1.0$ (Fig. 14.)

V_T	$VA_{2T} = V_{s1}$	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.

Table 5
No-load branch currents $V_T = 1.0$ (Fig. 14.)

I_{s1}	I_1	I_2	$I_{r1} = I_{s2}$	$I_3 = I_4$	$I_5 = I_6$
0.11 +j1.30	0.00 +j0.31	0.11 +j0.98	0.08 +j0.66	0.03 +j0.33	0.04 +j0.33

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

Table 6
No-load node voltages $V_T = 0.9$ (Fig. 14.)

V_T	$VA_{2T} = V_{s1}$	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.

Table 7
No-load branch currents $V_T = 0.9$ (Fig. 14.)

I_{s1}	I_1	I_2	$I_{r1} = I_{s2}$	$I_3 = I_4$	$I_5 = I_6$
0.10 +j1.17	0.00 +j0.28	0.10 +j0.88	0.07 +j0.59	0.03 +j0.29	0.03 +j0.29

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.

Table 8
No-load node voltages $V_T = 1.0$ (Fig. 14.) with
25 kVAr shunt reactor installed at nodes V_{r1} , V_{s2} and V_{r2}

V_T	$VA_{2T} = V_{s1}$	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_5 , are with shunt lower Table 9.

Table 9
No-load branch currents $V_T = 1.0$ (Fig. 14.) with
25 kVAr shunt reactor installed at nodes V_{r1} , V_{s2} and V_{r2}

I_{s1}	I_1	I_2	$I_{r1} = I_{s2}$	$I_3 = I_4$	$I_5 = I_6$
0.08 +j0.78	0.00 +j0.31	0.08 +j0.47	0.05 +j0.31	0.02 +j0.16	0.03 +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.

Table 10
Node voltages $V_T = 0.9$ (Fig. 14.)
140 kVA load demand at 0.85 power factor

V_T	$VA_{2T} = V_{s1}$	V_{r1}	V_{s2}	V_{r2}
0.9	0.9 -j0.02	0.85 -j0.05	0.85 -j0.05	0.84 -j0.06

Table 11
Branch currents $V_T = 0.9$ (Fig. 14.)
140 kVA load demand at 0.85 power factor

I_{s1}	I_1	I_2	$I_{r1} = I_{s2}$	$I_3 = I_4$	$I_5 = I_6$
0.66 +j0.22	0.19 +j0.11	0.47 +j0.11	0.31 +j0.06	0.16 +j0.04	0.15 +j0.02

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_2 at peak-load, Table 13, is with a 24 kW BESS at node V_{r1} and V_{r2} , Fig. 14, lower than the line current I_2 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 lagging 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.

Fig. 15. A line shunt reactor transformer with a battery energy storage system connected to the secondary winding. Switch SW_1 across tertiary winding T_1 with Fig. 11 is not conducting.

Table 12

Node voltages (Fig. 14.)

Supply side peak load shaving for a 27 kVA ESS at node V_{r1} and V_{r2}

V_T	$VA_{2T} = VS_1$	V_{r1}	VS_2	V_{r2}
0.9	0.91 -j0.02	0.91 -j0.08	0.91 -j0.08	0.92 -j0.04

Table 13

Branch currents (Fig. 14.)

Supply side peak load shaving for 27 kVA ESS at node V_{r1} and V_{r2}

IS_1	I_1	I_2	I_3	$Ir_1 = IS_2$	I_4	$I_5 = I_6$
0.41 +j0.59	0.19 +j0.12	0.21 +j0.46	0.02 +j0.19	0.20 +j0.28	0.17 +j0.07	0.03 +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].

Fig. 15. A single-phase distribution transformer equipped with an autonomous thermal overload protection scheme

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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