# *Distribution Substation Dynamic Reconfiguration and Reinforcement - Digital Twin Model*

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*Abstract*— **The proliferation of electric vehicles will increase demand and alter the load profiles on final distribution substations quicker than traditional reinforcement techniques can respond. As it is nontrivial to determine in advance, to street level granularity, where and when vehicles will charge, a more flexible approach to substation reinforcement is preferable to the existing rip-out-and-replace technique for an overloaded transformer. Distribution Substation Dynamic Reconfiguration (DSDR) combines reinforcement using parallel transformers with reconfiguration algorithms to flexibly operate the substation in the face of uncertain loading conditions, by dynamically switching transformers in and out of service. This paper presents a digital twin and a benchtop scale model of the DSDR substation for the development and evaluation of such algorithms, along with two algorithms for optimizing substation technical losses. Initial results show that on a single tested substation model, efficiency increased by 5.40% with Net-Zero Year 2050 load profiles versus traditional reinforcement.**

***Keywords— Smart Substation, Digital Twin, Network Reinforcement, Technical Losses***

## I. INTRODUCTION

The ambitious Net Zero 2050 target of the UK has driven a commitment to banning the sale of internal combustion engine vehicles by 2030. In turn, it is forecast that 30 million new Electric Vehicles (EV) will be on the road, charging from the electricity distribution networks, by 2025. The uplift caused by these being connected at Low Voltage (LV) will approximately double the demand of the existing heating and appliance base load at final distribution substations. Many final substations will therefore need to be reinforced, and at a rate much faster than previously anticipated, with bottlenecks possible in the supply of transformers and skilled labor which could easily delay mass EV uptake. Furthermore, it is challenging to determine where and when these EV's will charge with sufficient precision to ensure that the correct substations are reinforced in good time.

The solution proposed in this paper seeks to address this challenge by effectively monitoring, understanding, and preparing substations for this change through a combination of pre-emptive parallel transformer reinforcement, and post-reinforcement real-time substation reconfiguration for optimal operation. A Digital Twin (DT) model of the post-reinforcement substation is developed, and used to formulate optimization algorithms required to implement the solution.

The outcome is, according to the existing literature, the first Distribution Substation Dynamic Reconfiguration Digital Twin (DSDR DT) capable of performing experiments in real time, which can operate either entirely virtually by simulating substation load flow or integrate with physical instruments in a bench top scale model DSDR substation, to accelerate the route to pilot trials and ultimately Business-as-Usual deployment of this solution.

UK final distribution substations transform Medium Voltage (MV) of 6.6 kV – 33 kV to 400 V, from which LV customers are suppled via feeders and service cables; these typically contain one MV/LV (ONAN cooled, three-phase) transformer, pad or pole mounted, rated between 100 kVA – 1 MVA. Whilst traditional reinforcement would remove the existing transformer for recycling and replace it with one of a higher rating, the DSDR reinforcement method calls for an identically rated transformer to be fitted in parallel with the existing, with telecontrol switches on the MV and LV sides of each as shown in Fig.1.

Whilst the concept of economic operation of parallel transformers through manual seasonal switching was introduced in 1987 [1], a model transformer with multiple switchable windings presented in 2009 [2], and reconfiguration of primary substations with existing multiple parallel transformers to 'minimize annual energy losses while avoiding frequent

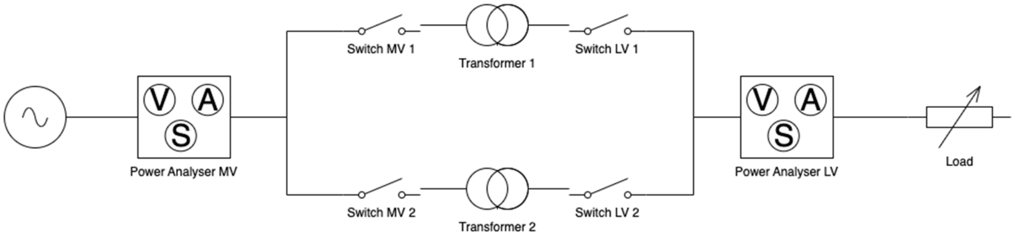

Fig. 1. Single line diagram of Distribution Substation Dynamic Reconfiguration circuit

transformer switching' investigated in 2018 [3], this is the first work investigating DSDR as a reinforcement strategy in final distribution substations serving LV customer loads.

The advantages of such an approach are that existing transformers are no longer prematurely sent for recycling; reinforcement can be carried out pre-emptively, with transformers seamlessly moved between substations if load materializes spatially other than forecasted; and the substation can be dynamically reconfigured by switching transformers in and out of service by an optimization algorithm. Objective functions for this may include minimizing technical losses, managing harmonic voltages, or providing frequency support through Conservation Voltage Reduction (CVR). This paper will present a Digital Twin (DT) model and Bench Top Scale Model (BTSM) of a DSDR substation, two algorithms for minimizing losses in a DSDR substation, and the initial results for both algorithms.

## II. DIGITAL TWIN

Digital Twins (DT) are typically defined as a real-time virtual representation of a physical asset, including a simulation of some of the asset's attributes [4], leading to the generic DT architecture shown in Fig.2. On the left of the diagram, the 'External Systems' block represents software which is not part of the core DT real-time functionality such as data storage systems, and hardware with which the DT may communicate such as sensors connected to the physical asset which the DT twins.

These are interfaced to the DT through the Orchestrator component, which is responsible for real-time communications, coordination, and user interaction. The Simulator component of the DT, shown at the right of the figure, is responsible for modelling in real-time one or more parameters of the physical system represented by the digital twin, in response to system state collected by the orchestrator from external systems.

In this work a DT is developed which can host DSDR algorithms that operate on either a physical substation or a simulated substation model, accelerating the route from algorithm development, through evaluation, to field trials and business-as-usual deployment.

Fig. 2. Generic Digital Twin architecture

Fig.3 shows the DSDR DT software architecture, at the center of which is an in-memory database holding real-time state of any connected physical instruments (such as power meters) and virtual-instrument supplied measurements from an OpenDSS model of the DSDR substation. Fig.4 shows the connections required to interface the DT software with a physical substation.

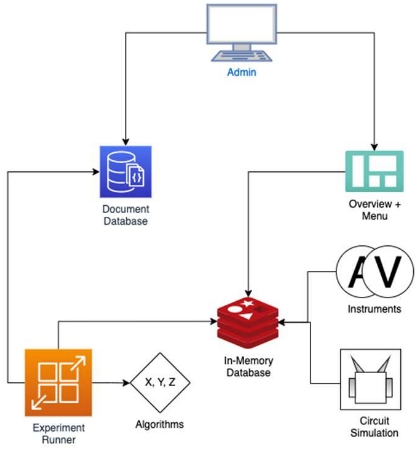

Fig. 3. DSDR Digital Twin software architecture

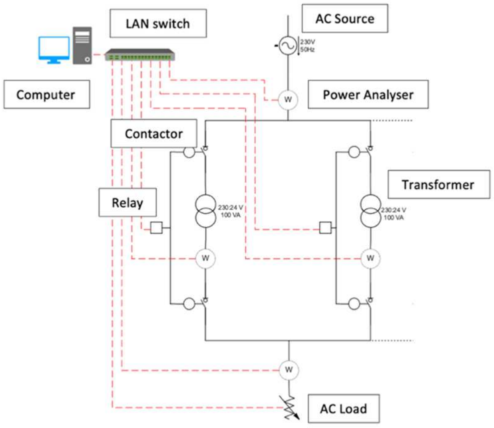

Fig. 4. Connections to physical substation model

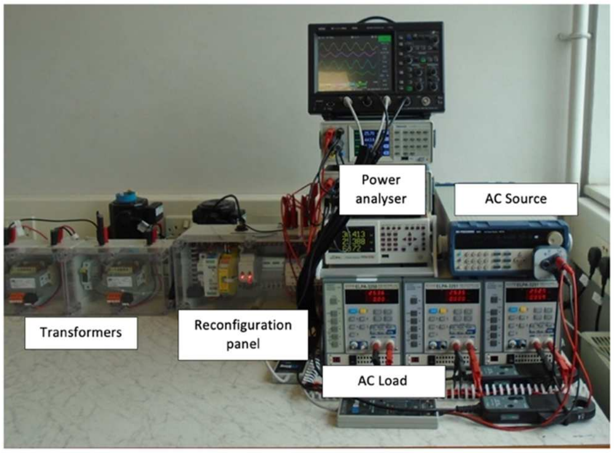

Fig. 5. DSDR Bench Top Scale Model

## III. BENCH TOP SCALE MODEL

A Bench Top Scale Model (BTSM) of a DSDR substation shown in Fig.5 was constructed comprising of a programmable AC source, load, and power analyzer, two 100 VA (AN-cooled, single phase) 230:24V transformers, contactors to reconfigure the transformers in or out of circuit, and a programmable relay, all controlled by a PC running the DSDR DT software. A full system specification is given in Table I.

The transformers' equivalent circuit parameters shown in Table II were determined from open-circuit and short-circuit tests then loaded into the DT software, for use when running in DT simulation mode, and separately for use by the optimization algorithms.

TABLE I. BENCH TOP SCALE MODEL SYSTEM SPECIFICATION

| Function | Manufacturer | Model | Rating |
|---|---|---|---|
| Transformer | Block | STS-100/23/24 | 100 VA |
| Power Supply | RS-Pro | 136-8308 | 24 V / 30 W |
| Relay | Brainboxes | ED-538 | 5 A / 30 V |
| Indicator | Schneider Electric | A9E18335 | 12 V – 48 V |
| Contactor | Schneider Electric | LC1D18BD | 18 A / 24 V coil |
| AC Source | BK Precision | 9801 | 300 VA |
| Power Analyser | Newton's 4th | PPA1530 | 20 A / 1000 V |
| AC Load | ETPS | ELPA-3250 | 20A / 60 V / 300 W |
| LAN Switch | Netgear | GS308 | 8 Ports |
| Ethernet to Serial adapter | Brainboxes | ES-701 | 4 x RS 232 ports |

TABLE II. BENCH TOP MODEL TRANSFORMER EQUIVALENT CIRCUIT PARAMETERS

| Parameter | Symbol | Unit | No. 1 | No. 2 |
|---|---|---|---|---|
| Primary winding resistance | R1 | Ohms | 19.765 | 19.212 |
| Primary winding reactance | jX1 | Ohms | 1.940 | 1.948 |
| No-load loss resistance | Rc | Ohms | 8986.04 | 10341.47 |
| Magnetizing current reactance | jXm | Ohms | 1007.33 | 1177.55 |
| Secondary winding resistance | R2 | Ohms | 0.251 | 0.244 |
| Secondary winding reactance | jX2 | Ohms | 0.0246 | 0.0248 |
| Combined winding resistance | Req1 | Ohms | 39.53 | 38.436 |
| Combined winding reactance | jXeq1 | Ohms | 3.88 | 3.90 |

The two algorithms implemented for the experiments are as follows; a threshold algorithm uses binary decision logic to select a heuristically efficient reconfiguration state of the substation at each load step. The threshold value of substation load in kVA, about which the substation will change its configuration between single or parallel mode, was set to 50% of the substation's total kVA rating.

A model-based algorithm uses OpenDSS simulations of the substation in each reconfiguration state to select the theoretically optimal single or parallel operating mode. At each load step, load flow simulations are performed to determine the modelled substation efficiency at the measured operating point, and the permutation which yielded the highest modelled substation efficiency is actuated in the substation.

## IV. RESULTS

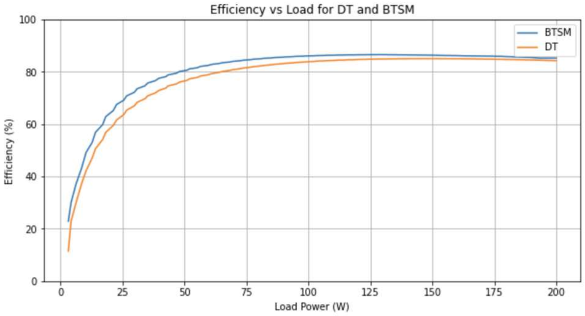

Fig. 6. Validation of DT and BTSM substation efficiency

TABLE III. BASELINE AND LOSS MINIMIZATION ALGORITHM PERFORMANCE FOR RESIDENTIAL LOAD

| Case | Algorithm | Mean Efficiency | Percentage Efficiency Delta (vs Case A) |
|---|---|---|---|
| A | None | 81.50 % | 0 % |
| B | Threshold | 83.81 % | 2.31 % |
| C | Model-Based | 84.76 % | 3.26 % |

TABLE IV. THRESHOLD AND MODEL-BASED ALGORITHM OVERALL PERFORMANCE WITH NET-ZERO YEAR 2050 LOADS

| Scenario Year | Threshold Algorithm Efficiency Improvement | Model-Based Algorithm Efficiency Improvement |
|---|---|---|
| Net-Zero 2050 | 4.06% | 5.40% |

The substation total efficiency with both transformers in parallel was recorded over the full range of rated load, on the DT with OpenDSS model and the BTSM with physical transformers, which validated the experimental setups without any algorithm applied, as shown in Fig.6.

A typical UK residential one-day load profile, scaled with the peak value equal to the substation nameplate rating, was replayed on the DT substation under; a) a baseline case with both transformers operating in parallel, b) the threshold algorithm, and c) the model-based algorithm. The results are given in Table III – these were validated using the Bench Top Scale Model.

EV charging and residential loads at the scale expected in Net-Zero Year 2050 were combined as shown in Fig.7, for each standard UK electricity system season-day. The figure shows each profile normalized to the original (non-reinforced) substation rating represented by the dashed line.

The experiments described above were repeated on the Digital Twin model for the base case and both algorithms, with each load profile. The resulting aggregated resulting substation efficiency improvements are given in Table IV.

## V. CONCLUSIONS AND FUTURE WORKS

The DSDR reinforcement method, when combined with threshold and model-based algorithms for optimizing technical losses, increased substation efficiency by 4.06% and 5.40% respectively. Scaling up the model-based algorithm's 5.40% efficiency improvement to all final distribution substations across the UK, based on the forecasts of combined domestic and EV charging annual electricity demand of 200 TWh by 2050, DSDR has the potential for ~10 TWh of system efficiency savings. Planned future works include further validating the DSDR approach using a modified version of the IEEE 33-node distribution system.

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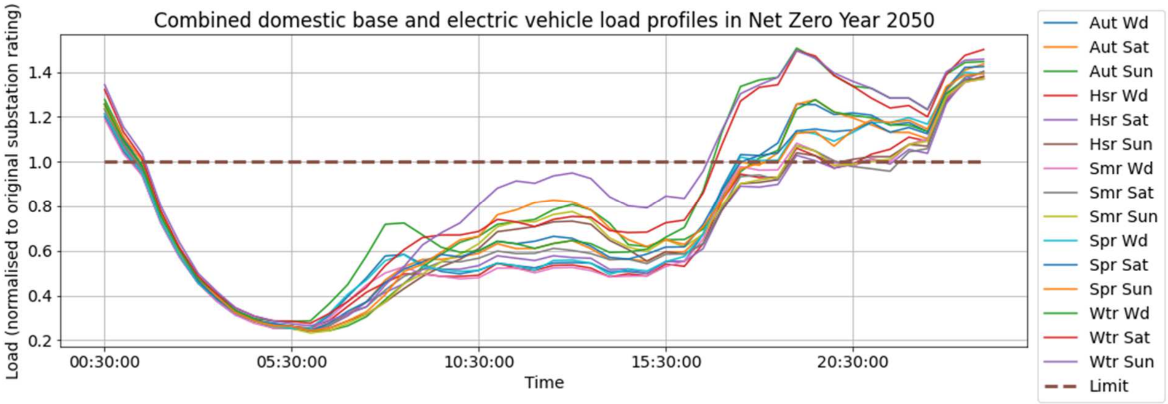

Fig. 7. EV charging and residential loads at the scale expected in Net Zero year 2050