

LOCAL CONTROLLER MODEL TO LOAD BALANCE IN URBAN MICROGRIDS USING A TIMED HIERARCHICAL PETRI NETS APPROACH

JOSÉ R. SICCHAR*, JOSÉ R. SILVA†, CARLOS T. DA COSTA JR.‡, VITOR F. D.S. GADELHA*, LUCAS J. D.S. BATISTA*

*1200, Darcy Vargas Av., Control Automation Department, EST
University of the Amazon State
Parque Dez, CEP.69050-020, Manaus, Amazonas, Brazil

†223, Prof. Melo Moraes Av., Mechatronic Department, EPUSP
University of São Paulo
Butantã, CEP.05508-900, São Paulo, Brazil

‡01, José Corrêa Av., ITEC
Federal University of Pará
Guamá, CEP. 66075-900, Pará, Brazil

Emails: jvilchez@uea.edu.br, reinaldo@usp.br, cartav@ufpa.br, vitorfgadelha@gmail.com, ljdsb.eng16@uea.edu.br

Abstract— Smart grids raised a great demand for special services and automatic control, particularly to load balance on low-voltage consumers grid, which stands out for ensuring stable states between phases in the secondary grid. This paper presents a new system design approach in order to automate the phase load balancing process, as an alternative system control to urban microgrids. The control system is based on combined algorithms that process the load unbalances identification in the phases of the grid, the load consumption classification and forecast of the consumer units, and the optimization of the selection consumption units to be switched in feeders. The system design validation is performed using a Timed Hierarchical Petri net. The result produces an efficient automated workflow of tasks to the phase load balancing, based on automatic load switching and ensure the load stability in the grid and minimize the load average unbalance.

Keywords— Fuzzy Systems, Microgrids, Phase Load balancing, Timed Hierarchical Petri nets.

1 Introduction

In electric distribution grid the legacy low-voltage (LV) system has been enhanced by a modern architecture called *urban microgrids*(UMG) (Siirto et al., 2015) where a cluster of residential consumers are integrated in microgrids with composed by power micro-sources, storage system, domestic loads (Mariam et al., 2016). The supervision and control of the energy flow is managed by the **Micro-Grid Control Center**(MGCC) and it manages the energy consumption loads and the power injection from the multiples microgrids in order to maintain the load balancing in the phases of the secondary grid of the urban microgrid (Wu et al., 2018).

However, in the legacy LV system the problem of load unbalance feeders is a drawback, caused mainly by domestic loads generated by individual consumers. It affects the grid feeders stability, and the quality of the energy supplied (Samet et al., 2018). To face that local solutions are presented, based mainly on supervision and control algorithms that optimize the power and electric current flow. These solutions are part of the MGCC (Strasser et al., 2015).

In classic low-voltage circuit, with only small energy consumers, these control algorithms focuses on load balancing system based on **phase load balancing** (PLB) procedure (Siti et al.,

2007). Such algorithm is applied to the secondary grid, switching the consumers' feeders most loaded with the grid feeders with lower unbalance level, allowing recovery the grid steady state and decreases unbalance in feeders (Shahnia et al., 2014), (Siti et al., 2011).

On the other hand, in urban microgrids (UMG), algorithms guide the electric current injection into the grid transferring additional current to some unbalanced phase, managed by the MGCC system and processes optimal integration of the energy flow from the micro-sources (Samet et al., 2018), but it not performs efficiently the synchrony between grid electric current and injected current, increases harmonics and reactive power into grid, affecting the quality and stability of the net power supplied to the consumers (Zecchino et al., 2015). In addition, this new system requires substantial financial investment for energy micro-sources implementation in urban area, especially in developing countries such as Brazil and others belonging to the BRICS (Nunna et al., 2016).

In the Brazilian legacy low-voltage system, do not present a fully integrated and automated load balancing system (Gomes et al., 2017). There is only a partially automated flow, where the load balancing algorithm does not automatically interact with the grid supervision center. It can slow down the immediate intervention with any

eventual emergency of some great load unbalance in feeders, or even in the transformer protection. Therefore, there is a gap in formal modeling for automates procedures for the load balancing in the LV grid.

This article presents a new model of a control system to automate the load balancing procedures, in the legacy Brazilian LV grid. The main aim is to develop a smart interaction between the load balancing procedures as an smart control system, with the grid supervision center to solving the unbalance grid feeders problem. We expect to obtain an efficient automation flow. The control system is based on a combining algorithms that composed four steps: i) to identify the load unbalances in the grid feeders, ii) to detect the unbalanced consumer units, iii) to forecast load consumption in the unbalanced consumers units, and also iv) to optimize the consumers units selection to switch in the grid feeders. As a practical application, a case study will be developed in a circuit of Manaus city, using the consumption data of the users and the grid feeders by simulation. As a result, it is expected that the proposed system will not only provide an efficient and an automated reliable workflow to the load balancing process in the legacy grid, but may also became it in an alternative load balancing control procedure at the MGCC in the urban microgrids context.

This article is organized as follows, Section 2 explains the background of the proposed model system; Section 3 develops the load balancing control architecture; Section 4 shows the results and discussion of the dynamic system validation; Section 5 presents finally the conclusions.

2 Background

In this section we addressed the related issues with the proposal. First, we present a specific state of art related with the load balancing applied in the legacy LV grid. Then we address some definitions about Timed Hierarchical Petri nets to use in this research.

2.1 State of Art

In the legacy low voltage grid "unbalance feeders" constitutes a power consumption flow problem as shown in Fig.1. Generally, it is caused by the growing disorder and by the unplanned consumption of domestic loads in residences (Gomes et al., 2017). In extreme situations this can affect the power supply, especially in what concerns the equilibrium between grid feeders; Transformer can be burned if this problem is not solved in the proper time (Zecchino et al., 2015).

Phase Load Balancing based on "Automatic Load Switching" is an interesting approach to address this problem (Safitri et al., 2016). That

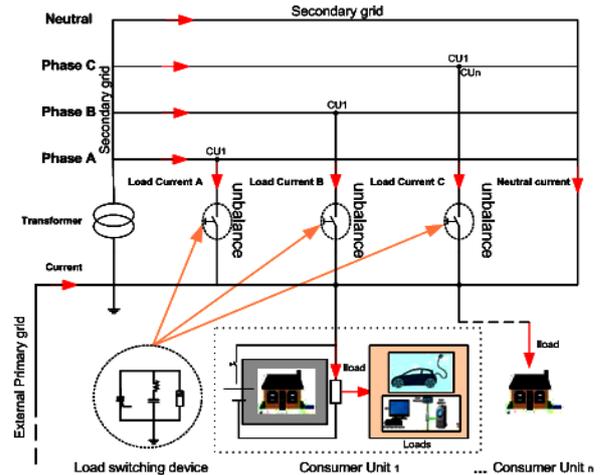


Figure 1: Load unbalance in secondary grid.

could cope with a common situation where most consumers load feeders are switched to a feeder with a lower load level using some electronic switching device as shown in Fig.1, which uses a control algorithm to automate the minimization of load and electrical current (Siti et al., 2011) or instead voltage and load (Shahnia et al., 2014).

In spite of the load balancing introduced by distributed resources power injection (Wu et al., 2018) we will use in this paper an automated approach based on the phase load balancing use a control system based on combined algorithm (Sicchar et al., 2017). In this specific case, we addressed the system design of this control system using a Timed Hierarchical Petri net to achieve an automated and efficient flow for phase load balancing in the LV grid.

2.2 Timed Hierarchical Petri net

The formal models of complex systems as control systems of urban microgrids are validated from static and dynamic point of view by Petri Nets property analysis and workflow. The use of Petri Net extensions could facilitate that process. Between the extensions we would detach hierarchy and the introduction of time. The first would be advisable to treat large systems and the later to open space to optimization in the service provide to the unit clients (concerning specifically the LBS). Thus, the use of Petri nets (PN) is suitable because it is a formal method which is plenty adapted to the goal oriented approach to requirements, and due to its wide range of environments to do the modeling and dynamic simulation (Xing et al., 2012).

The hierarchical approach would also fit the architecture imposed to the retrofitted (and automated) legacy system and the identification of points to couple the proposed system. In this article we will consider a simple case of Petri Nets

with time slice, or fixed time intervals. In addition, the dynamic simulation with time intervals is important because it allows to emulate the coupling with the general system, looking for conflicts and deadlocks in this process. Therefore, the use of Timed Petri nets (TdPN) (Popova-Zeugmann, 2013) becomes interesting to simulate the flow of operations in the proposed system, to emulate its integration with the central control in the transformer and to check its service providing to the physical plant of unit clients. In an enhanced model we could include other alternative sources of energy which would be called a secondary grid.

A Timed Hierarchical Petri net (TdHPN) can be defined as follows.

- *Definition 2.2.1. Timed Hierarchical Petri Net.* A TdHPN is a 7-tuple, according to expression 1:

$$N = (P, T, A, w, M_0, F, I) \quad (1)$$

Such that

1. The 5-tuple $N = (P, T, A, w, M_0)$ is a marked Petri net, where:
 - * P is a finite set of places, $P \neq \emptyset$;
 - * T is a finite set of transitions, $T \neq \emptyset$;
 - * $A \subseteq (PxT) \cup TxP$ is the set of arcs from places to transitions and from transitions to places;
 - * $w : A \rightarrow \{1, 2, 3, \dots\}$ is a weight function on the arcs, and
 - * M_0 is the initial marking of the PN.
2. F is a function *Place Bounded Substitution* that ensures that a sub-net Y limited by transitions can be replaced by a place s generating another net: $N' = \{P', T', F'\}$, where:
 - * $P' = P \setminus S_y \cup \{s\}$, where S_y is the set of places in Y ;
 - * $T' = T \cup T_Y$, where T_Y are the transitions in Y ;
 - * $F' = F \setminus Int(Y)$, where $Int(Y)$ is the inner arcs set of Y .
3. $I : T \rightarrow \mathbb{Q}_0^+ \times (\mathbb{Q}_0^+ \cup \{\infty\})$ where for each $t \in T$, with $I(t) = [I_i(t), I_j(t)]$ it holds that $I_i(t) \leq I_j(t)$ (Popova-Zeugmann, 2013).

3 LBC system design

The proposed control system is called "load balancing control" system (LBC), and it is based on a system of combined algorithm with four steps according Fig.2, which aims to automate the procedures related to the identification of load unbalances in the grid feeders and in the consumer

units, as well as in the selection of the consumption units arrangement for the switching process, which is based on the load forecast of the unbalanced consumption units (Sicchar et al., 2017). Then, the system design will be based on this architecture and also in the general flowchart as shown in Fig.3.

3.1 LBC architecture

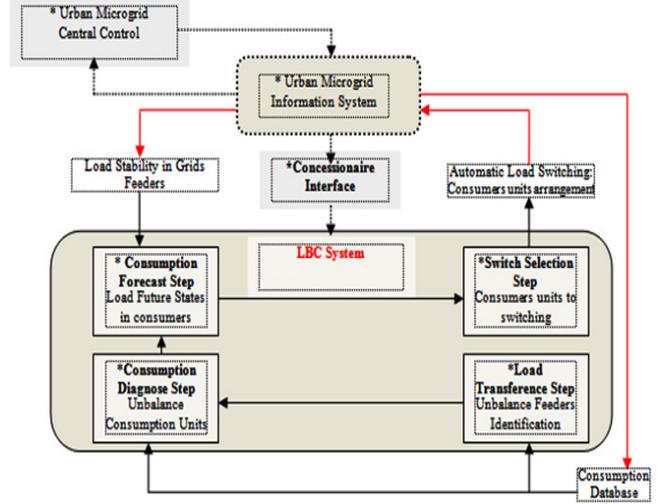


Figure 2: LBC Architecture.

The LBC system has the architecture showed in Fig.2 that is composed by four steps as follow:

- **Load Transference Step (LTS).** Which is based on a *Mamdani Fuzzy* inference that identifies the load unbalances in grid feeders. It identifies the different levels of load amount in the feeders, based on some rules between the input of this sub-system, called "load levels" and the output, called "load amount to transfer" (Siti et al., 2011).
- **Consumption Diagnose Step (CDS).** Which is only enabled when is detected some "load unbalances" in the grid feeders. This is based on also a *Mamdani Fuzzy* inference but addressed to detect the consumption units with unbalances levels in their phase(s) according of its load consumption database. The inference machine is based on four inputs (energy consumption, energy consumption variation, energy price variation, and temperature variation) that determine the load variation in the phases (Sicchar et al., 2017).
- **Consumption Forecast Step (CFS).** Which is based on Markov chains algorithm that performs the future levels of the monthly load consumption with twelve-steps forward. This step is applied only in the consumption units with unbalances. The forecast process is based

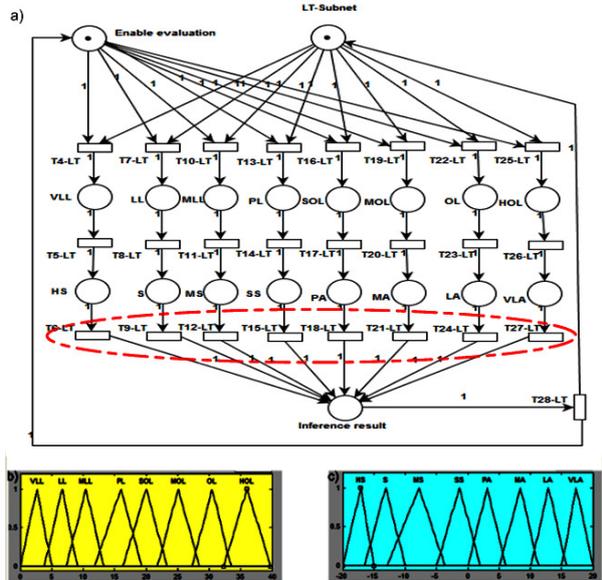


Figure 6: Load Transference subnet: a) LT PN; b) Membership function for input parameters; c) Membership function for output parameters.

Table 1: Input Fuzzy Nomenclature

Inp	Desc	Fuzzy Nom	Kw range
1	Very Less-Loaded	VLL	0 -5
2	Less-Loaded	LL	3, 8 -9, 0
3	Medium Less-Loaded	MLL	7, 3 -13, 3
4	Perfectly Loaded	PL	11, 8 -19, 3
5	Sightly Over-Loaded	SOL	16, 3 -23, 3
6	Medium Over-Loaded	MOL	21, 7 -28, 4
7	Overloaded	OL	21, 2 -33, 4
8	Heavily Overloaded	HL	32, 3 -39, 8

LT Petri net validation

- Reachability graph. Figure 7 shows the reachability graph of the LT PN. It represents the PN reachable diagram obtained from its initial state "S₀" highlighted by the red arrow, that also represents the initial marking of this PN.
- Place Invariant analysis. Equation 4 shows the first P-invariant: "Enable evaluation" stayed invariantly before the all evaluation of "load" and "load transfer". This workflow represents and validates the main cycle of the LT subsystem. Thus, the complete marking condition of this sequence were be equal to "1".

$$\begin{aligned}
 &M(Enable_{eval}) + M(VLL) + M(HS) + \\
 &M(LL) + M(S) + M(MLL) + M(MS) + \\
 &M(PL) + M(SS) + M(SOL) + M(PA) + \\
 &M(MOL) + M(MA) + M(OL) + M(LA) + \\
 &M(HOL) + M(VLA) + \\
 &M(Inferenceresult) = 1
 \end{aligned} \tag{4}$$

Table 2: Output Fuzzy Nomenclature

Out	Desc	Fuzzy Nom	Kw range
1	High subtraction	HS	-20 to -15, 3
2	Subtraction	S	-16, 5 to -10
3	Medium subtraction	MS	-12, 9 to -3, 6
4	Slight subtraction	SS	-4, 9 to -2
5	Perfect Addition	PA	0 - 6
6	Medium Addition	MA	5, 0 - 11, 2
7	Large Addition	LA	10, 1 - 15, 7
8	Very large addition	VLA	15 - 20

Table 3: Fuzzy rules

Rule	If input	is	then output	is
1	"Load"	VLL	"Transfer"	VLA
2	"Load"	LL	"Transfer"	LA
3	"Load"	MLL	"Transfer"	MA
4	"Load"	PL	"Transfer"	PA
5	"Load"	SOL	"Transfer"	SS
6	"Load"	MOL	"Transfer"	MS
7	"Load"	OL	"Transfer"	S
8	"Load"	HOL	"Transfer"	HS

On another hand, equation 5 shows the second P-invariant: "LT subnet" stayed invariantly before also the all evaluation of "load", "load transfer" and the "Inference result". This workflow represents and validates the second cycle of the LT subsystem. Thus, the complete marking condition of this sequence were be equal to "1".

$$\begin{aligned}
 &M(LT - Subnet) + M(VLL) + M(HS) + \\
 &M(LL) + M(S) + M(MLL) + M(MS) + \\
 &M(PL) + M(SS) + M(SOL) + M(PA) + \\
 &M(MOL) + M(MA) + M(OL) + M(LA) + \\
 &M(HOL) + M(VLA) + \\
 &M(Inferenceresult) = 1
 \end{aligned} \tag{5}$$

LBC system simulation

The proposed system was submitted to a simulation study with real data, in a LV circuit with load consumption data of 51 consumers, a transformer of 110 Kilo-Volts-Amperes (KVA), with almost 67 Kilo-Watts (KW) of active power. All performance evaluations was developed using Matlab, and we considered three situations: "Unbalanced" in the circuit, the "Legacy method" for load unbalance and the "LBC system". We used the methodology indicated by Siti (Siti et al., 2011), in order to verify only the level of correction of load unbalance in the grid feeders, through the "Load absolute unbalance" (LAU) (Sicchar et al., 2017).

Figure 8-(a) shows the "Load in the Grid Feeders", in three scenarios: original or "unbalanced"

S0 [Tangible State]
Marking: {1, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0}
Edges From: S17 (T28-LT)
Edges To: S1 (T7-LT); S2 (T4-LT); S3 (T23-LT); S4 (T22-LT); S5 (T19-LT); S6 (T16-LT); S7 (T13-LT); S8 (T10-LT)

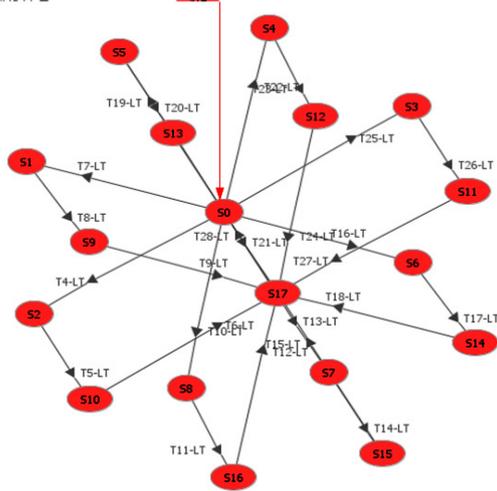


Figure 7: Reachability graph of the Load Transference subnet.

state, with load balance "Legacy method" application and the proposed system. Then, it was obtained a better load balance in feeders with the LBC system (red arrows): 20 KW in feeder A, 21 KW in feeder B and 20 KW in feeder C.

At last, Fig.8-(b) shows the boxplot of the LAU which represents in fact the unbalanced degree (in KW) in the grid feeders. Thus, the LBC system caused LAU of 0,67 % less than 8,67 % of the Legacy method; therefore, proving its efficient validation.

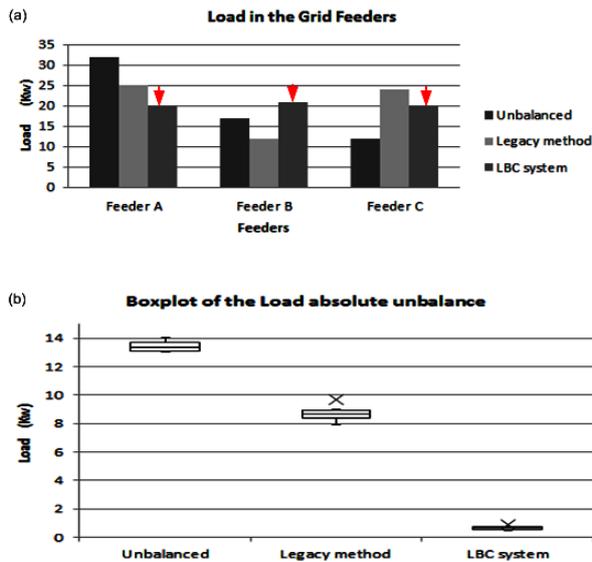


Figure 8: LBC system validation: a) Load in the Grid Feeders; b) Load absolute unbalance.

5 Conclusion

A dynamic model of a load balance controller was developed for the Microgrid Central Controller system of an urban microgrid, by employing the Time Hierarchical Petri nets approach.

The system design developed allowed to integrate efficiently the automate flow of the algorithms system of the load balancing control system. We evaluated the dynamic system design validation of the integrated hierarchical PN, as well as, in the load transfer subnet by reachability graph and the place invariants analysis. It was obtained the tangibility of the states of the hierarchical PN and also in the Load transfer subnet. In addition, it was obtained cycles that ensure the place-invariants in both networks. Thus, it was obtained an efficient validation of the main PN and the inference rules of the load transference subnet. At last, were obtained by simulation in a circuit of a low-voltage grid, a good performance of load absolute unbalance, which was better compared to the result of the legacy method.

Future work will develop a system design of a load flexible control system, from the voltage drop modeling by the load flow, and we will considered also the voltage unbalances in load balance performance.

In addition, we will considered in the same control system, the current injection from microgrids for ensure efficiently the load management consumption and the load greater stability in urban microgrids.

Acknowledgements

The authors thank to UEA, UFPA, USP and FAPEAM, for allowing scientific achievement of this proposal.

References

- Gomes, R. C. S., Silva, J. R., da Costa Jr, C. T. and da Silva, P. R. N. (2017). Automation meta-system applied to smart grid convergence of low voltage distribution legacy grids.
- Mariam, L., Basu, M. and Conlon, M. F. (2016). Microgrid: Architecture, policy and future trends, *Renewable and Sustainable Energy Reviews* **64**: 477–489.
- Nunna, H. K., Saklani, A. M., Sesetti, A., Battula, S., Doolla, S. and Srinivasan, D. (2016). Multi-agent based demand response management system for combined operation of smart microgrids, *Sustainable Energy, Grids and Networks* **6**: 25–34.
- Popova-Zeugmann, L. (2013). Time petri nets, *Time and Petri Nets*, Springer, pp. 31–137.

- Safitri, N., Shahnia, F. and Masoum, M. A. (2016). Coordination of single-phase rooftop pvs in unbalanced three-phase residential feeders for voltage profiles improvement, *Australian Journal of Electrical and Electronics Engineering* **13**(2): 77–90.
- Samet, H., Azhdari, E. and Ghanbari, T. (2018). Comprehensive study on different possible operations of multiple grid connected microgrids, *IEEE Transactions on Smart Grid* **9**(2): 1434–1441.
- Shahnia, F., Wolfs, P. J. and Ghosh, A. (2014). Voltage unbalance reduction in low voltage feeders by dynamic switching of residential customers among three phases, *IEEE Transactions on Smart Grid* **5**(3): 1318–1327.
- Sicchar, J. R., da Costa Jr, C. T. and Silva, J. R. (2017). Controlador local de balanceamento de carga para μ grids, *XIII Simpósio Brasileiro de Automação Inteligente (SBAI), 2017* pp. 1–6.
- Siirto, O., Hyvärinen, M., Loukkalahti, M., Hämäläinen, A. and Lehtonen, M. (2015). Improving reliability in an urban network, *Electric Power Systems Research* **120**: 47–55.
- Siti, M. W., Nicolae, D. V., Jimoh, A. A. and Ukil, A. (2007). Reconfiguration and load balancing in the lv and mv distribution networks for optimal performance, *IEEE Transactions on Power Delivery* **22**(4): 2534–2540.
- Siti, W. M., Jimoh, A. and Nicolae, D. (2011). Distribution network phase load balancing as a combinatorial optimization problem using fuzzy logic and newton–raphson, *Electric Power Systems Research* **81**(5): 1079–1087.
- Strasser, T., Andrén, F., Kathan, J., Cecati, C., Buccella, C., Siano, P., Leitao, P., Zhabelova, G., Vyatkin, V., Vrba, P. et al. (2015). A review of architectures and concepts for intelligence in future electric energy systems, *IEEE Transactions on Industrial Electronics* **62**(4): 2424–2438.
- Wu, P., Huang, W., Tai, N. and Liang, S. (2018). A novel design of architecture and control for multiple microgrids with hybrid ac/dc connection, *Applied Energy* **210**: 1002–1016.
- Xing, Z., Hong, Z. and Yulong, L. (2012). A petri-net based context-aware workflow system for smart home, *Parallel and Distributed Processing Symposium Workshops & PhD Forum (IPDPSW), 2012 IEEE 26th International*, IEEE, pp. 2336–2342.
- Zecchino, A., Marinelli, M., Hu, J., Coppo, M. and Turri, R. (2015). Voltage control for unbalanced low voltage grids using a decoupled-phase on-load tap-changer transformer and photovoltaic inverters, *Power Engineering Conference (UPEC), 2015 50th International Universities*, IEEE, pp. 1–6.