LOAD BALANCING PROCESS ANALYSIS IN LOW VOLTAGE GRID USING PETRI NETS

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Abstract— Recent evolution of smart grids is causing a big demand for new operations and services, specially to the low voltage consumers grid. Among those processes, load balancing detaches for ensuring stable states between feeders.This paper presents some results about the design of an automated process for load balancing feeders in final consumption units of a small urban smart grid using a Timed Hierarchical Petri net. The main objective is to analyze the proposed system and establish an efficient and reliable process workflow to automate load balancing and ensure stability while minimizes intervention. As a result it improves the quality of power service to the low voltage final consumers.

Keywords— Smart Grids, Load Balancing,Timed Hierarchical Petri Nets.

Resumo— Recentemente a evolução das smart grids tem causado uma grande demanda de novos serviços,especialmente nos consumidores da rede de distribuição de baixa tensão. Entre os quais, está o processo de balanceamento de cargas nas fases dessa rede. Este artigo apresenta os resultados da modelagem de um processo inteligente formado por sub-processos específicos para o balanceamento de carga nas fases das unidades consumidoras finais, de uma pequena rede elétrica inteligente urbana usando redes de Petri Hierárquicas Temporizadas.O objetivo principal é analisar o sistema proposto e estabelecer um fluxo de processos eficientes e confiáveis para o balanceamento automático de cargas,com a finalide de garantir o equilibrio entre as fases, e melhorar a qualidade de energia ao consumidor final de baixa tensão.

Palavras-chave— Smart Grids, automação do balanceamento de carga, Redes de Petri Hierárquicas, Redes de Petri Temporizadas.

1 Introduction

The perspective of having smart grids became closer since new approaches, were developed to rely in small urban smart grid (SUSG)(Shahgoshtasbi and Jamshidi, 2014)or even to mix legacy system centered in hydropower with low voltage (LV) units.

Within this focus, load balance feeders is an important issue to the quality of energy providing service, and several direct algorithms were proposed (Shahnia et al., 2014), (Sharma et al., 2014),(Sicchar et al., 2015) which should now be arranged in an automated process.

This process, forms a set for energy consumption management system (EMS) in the inner architecture of SUSG, and also forms a functional flow for sub-processes such as the voltage evaluating stability and load imbalance into residential feeders, Huang et al. (2015), within SG vision.

Specifically, in LV circuits is observed a problem: FCU loads consumption cause imbalance in power and electrical current between feeders, Sharma et al. (2014). It affects the stability feeders grid, and energy quality supplied.

Some possibles alternatives, as like minimization losses are being developed as the Automatic Feeders Reconfiguration (AFR). It is applied in LV grid and decreasing considerably the power losses and imbalance between grid feeders, Siti et al. (2011), Shahnia et al. (2014).

However, alternatives aforementioned have a gap in formal modeling for load balancing system design. They do not present workflow validation for the AFR process, Alt et al. (2006), Wang et al. (2015).

Therefore, we suggest the Petri nets (PN) use to improve balancing process performance in LV grid.That is, through formal modeling system is possible to obtain some process that improves load balancing efficiency. PN represent in this work the structure and system architecture and workflow tasks and control in system.

This article, explains in second section background; the third section presents the proposal and system model;in fourth section shows the system design in PN;the fifth section presents design validation analysis with operational flow performance and its discussion; the last section presents the conclusion and future work lines.

2 Background

We have in this section, the background related research line of this work.First, we have specific review related load balancing algorithms development in LV grid. Then, we have also review about PN use in SG. It will addressed, some specific definitions of PN that will be important for the development of this proposal.

2.1 State of Art

As load balancing method within AFR context, we can mention the transfers overload concentrated technique (losses and loads) into specific feeder working from three-phase consumer FCU. It is based on minimizing current consumption achieved by *Fuzzy* machine inference and *Newton-Rhapson's* optimization algorithm, between power consumption and power variation in each feeder, Siti et al. (2011).

There is, another method focused only on single-phase FCU, which minimizing power and voltage consumption uses an hybrid genetic algorithm. In this case, also taking up load transfer but reconnecting single- phase FCU in same feeder in grid, with lower load level, Shahnia et al. (2014).

Also, we can mention the hybrid load consumption algorithm model for FCU in LV grids,based on the Unified Modeling Language (UML)-PN paradigm, Sicchar et al. (2011), which connects data acquisition, classification, programming and consumption forecast, and sending best selection for arrangement switching feeders in load balancing.

In this paper, we will continue load balancing FCU feeders model but based on hierarchical PN paradigm, using balancing diagnostic,current and load consumption prediction, minimization consumption and optimal arrangement sequence selection flow algorithms as hierarchical sub-processes in main PN.

Contributing, with achievement of efficient process in load balancing, which can be used as an alternative method and/or interface in existent LV grid and as support process in supervision center for a small urban smart grid (SUSG).

2.2 Definitions

- *Definition 2.2.1. Petri Net.*A Petri net structure is a directed weighted bipartite graph, Silva and del Foyo (2012):

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

where: "P" is the finite set of places,$P \neq \varnothing$. "T" is the finite set of transitions, $T \neq \varnothing$."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,$\cdots$} is the weight function on the arcs.

- *Definition 2.2.2. Timed Petri Net.*Defined by:

$$N = (P, T, A, w, M0, f) \quad (2)$$

where: (*P, T, A,w,M0*) is a marked Petri net, Silva and del Foyo (2012),f : $T \rightarrow R^{+}$ is a firing time function that assigns a positive real number to each transition on the net.

- *Definition 2.2.3. Hierarchical Petri net by Place Bounded Substitution.*In a PN structure give by:

$$N = (P, T, F) \quad (3)$$

There is, an Y sub-net which limited by place so the replacement of this Y sub-net, generates another net *N' = (P', T', F')*, where: i) *P'*= $P \setminus T \cup \{S_y\}$, S_y is the new element that replaces Y; ii) *T'*=$T \setminus Y$;iii)*F'*=$F \setminus$Int(Y),Int(Y)is the inner Y arcs set, Silva and del Foyo (2012).

3 Proposal

Aiming to improvement the load balancing process in LV grid, we propose in this article: a model of an intelligent process for FCU load feeder balancing in small urban smart grid, using a Timed Hierarchical Petri Net (THPN), in order to obtain reliably and efficiently workflow, formally validated.

The load balancing flow in current secondary grid, it is not scope of this work.Through, hierarchical PN will be performed validation of a new system design with inner sub-processes that make feeders reconfiguration,called "**DPMS**", which is explained in following sub-section.At where, algorithms of each processes form a system and service that supporting the final consumers.

The Timed transitions use in proposal model are intended to represent,the most realistic way possible an entire period by simulation processing system for FCU feeders balancing. In this particular case, takes a granular period of 60 minutes, i.e., seeking feeder reconfiguration lasting one hour depending on sample consumption obtained at 10 minute intervals derived from SUSG information system (which is not part of this work), that stores the consumption data of end users.

In this article, will be developed according to initial proposal of the authors, Sicchar et al. (2011) but having as a contribution a broad and integrated PN with hierarchical description of its sub-process. It will be based on the system developed to FCU energy consumption diagnose, Sicchar et al. (2015) however considering beyond imbalance diagnostic and consumption forecasting stage,more two stages: minimizing current consumption and switching sequence selection.

3.1 DPMS Architecture

The process system, is called "**DPMS**" because of its four stages or sub-processes:"Diagnose", "Prevision","Minimization" and "Selection", each with a specific algorithm. So, these formed the DPMS system.

Thus, the DPMS system has an architecture formed as mentioned above, four specific processing (whose specific algorithms are not covered in this article):

- Balancing Diagnose or only "**D**" stage, that identifies the imbalance level in each feeder, Watching two situations: "balanced feeder", thus having the algorithm operating finish; and "unbalanced feeder" that activates the remaining stages of system, in sequence, starting with the consumption forecast step.

- Prevision Consumption or simply "**P**" stage, which only is activate when an imbalance is identified (in some feeder). So, It forecasts the current and energy consumption in feeders and returning this processing to the SG information system, that later develops the energy future consumption matrix indicating the trend of consumption to the FCU.

- Minimization Consumption or just "**M**" stage, which procedure some combination of switching between feeders from the current and the future consumption of the energy and electrical current obtained by "P" stage. So, in order to minimize power losses effects and ensuring the equilibrium state in feeders.

- Switchin Sequence or only "**S**" stage, Which chooses the best switching combination from the "M" stage. This selection is based on a correlation ratio analysis between the real value of consumption and with their values from the minimization stage.So, the final processing is sent to the information system SG as switching sequence, to procedure in fact the AFR.

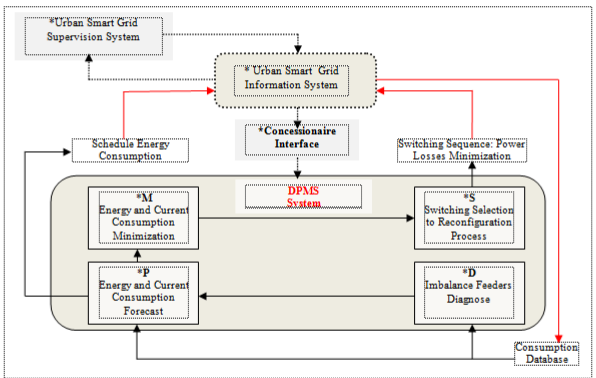

Figure 1: DPMS Architecture.

In Figure 1 It is shown the DPMS architecture system model, as support process for system information to supervision center in SUSG environment.It can also be inserted, as an interface in the existing secondary grid system.

Then, we have the operation flow of the DPMS system, which is shown in more details in Figure 2.This flow, is started from consumption data processing, and after consumption diagnosis are identified possible losses and load imbalances.

In positive case, starts energy and current consumption prediction process, in each FCU feeder. The main objective is to obtain,the future consumption matrix of electrical current.Furthermore, the prediction results serve to minimizing consumption process.

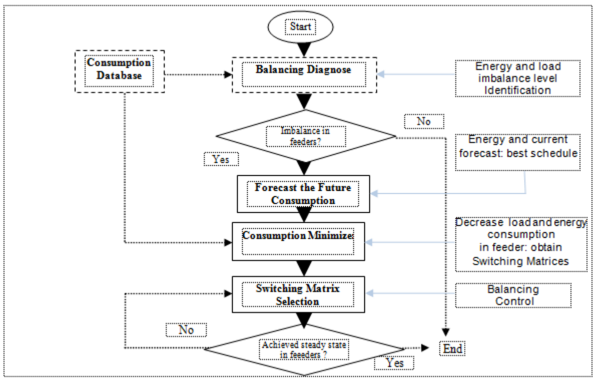

Figure 2: DPMS flowchart.

Followed by minimize consumption, looking for same sequences combinations of switching between feeders, which are calculated from current and future values of electrical current consumption.

Finally, switching matrix selection chooses which through, send best combination for FCU feeders balancing implementation. If imbalance minimizing process ends, otherwise proceeds in choosing other combinations for switching.

4 DPMS System in Petri Nets

In Figure 3 it is shown the "DPMS" system modeling in THPN. So, its describes the main PN of DPMS system. The hierarchical extension used is place bounded substitution (PBS) according to definition 2.2.2.

It is shown, the places that give sub-processes in main PN, that are described later in details.The DPMS system is connecting with a SUSG environment, which is compound of the Supervision Center, the Feeders Switching Control and the Consumption Data Record.So, system is activated through load balancing check application requirement in FCU feeders, activated by the Supervision Center of SUSG.

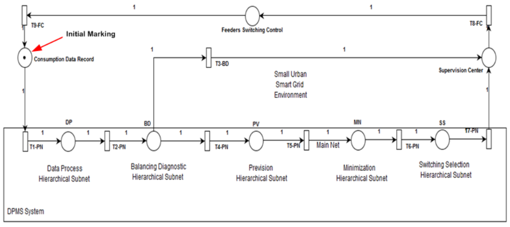

Figure 3: DPMS THPN:Main Petri net.

The inner workflow of DPMS system is formed as follows (see Figure 5):

- "**DP**".Data Process Hierarchical sub-net.Which has all statistical treatmen sub-processes.It is formed by:"L_1-DP",that classifies power, current and energy consumption data."L_2-DP",which calculates average consumption."L_3-DP", that forms discrete consumption states.
- "**BD**".Balancing Diagnose Hierarchical sub-net. It is contains:"L_4-BD",which inserts load and energy consumption as input variables in inference system."L_5-BD",that inserts load and energy consumption variation as input variable."L_6-BD", which inserts current consumption as output variable."L_7-BD"inserts inference rules."L_8-BD"obtain conditions to imbalance diagnose. **BD** exit has two conditions: FCU balanced "T_{13}-BD"and, No balanced FCU "T_{14}-BD" that actives **PV** place.
- "**PV**".Prevision Hierarchical subnet, with electrical current consumption sub-processes.It is formed by:"L_9-PV",which inserts discrete states consumption."L_{10}-PV",that calculates incidences consumption."L_{11}-PV", which obtain transition matrix."L_{12}-PV",that obtain forecast electrical current consumption.
- "**MN**". Minimization Hierarchical sub-net.It is formed by:"L_{13}-MN",which inserts measured electric current vector."L_{14}-MN",that inserts forecast current vector."L_{15}-MN", which forms minimization consumption vector."L_{16}-MN", that inserts minimization consumption formula."L_{17}-MN" which obtain arrangement switching matrices.
- "**SS**".Switching Selection Hierarchical subnet. It is contains:"L_{18}-SS",that inserts switching matrix values and correlation degree between forecast and measurement current, as like input variables in inference system."L_{19}-SS", which inserts load consumption as output variable."L_{20}-SS", that inserts inference rules."L_{21}-SS", which selects optimal switching matrix. After, this flow goes to supervision center (CS), and then feeder switching control (FC). The process goes through a measurement by data measurement (DM), whose flow is transferred as consumption data record (CDR).

5 Results-Validation analysis

In this section,we will show the validation results of DPMS system, modeled in THPN,using reachability graph, invariant analysis applied in Main DPSN THPN and also in Hierarchical DPMS THPN which shown all processes of system and also use siphon and traps analysis for validation workflow. For experimental results, was used as tool a free version of Pipe 4.3.0.

For simulation, timed transitions were used. It is distributed fixed time intervals, for each operation of sub-process,it was used T = 10 seconds,and for total integration operations add up to a full period of T = 60 seconds.

5.1 Main DPMS THPN validation

a) Reachability Graph. The Main DPMS Reachability graph is shown in Figure 4. So, it represents the PN reachable diagram obtained from Its initial state "S0" highlighted in red, that also represents initial marking of PN.

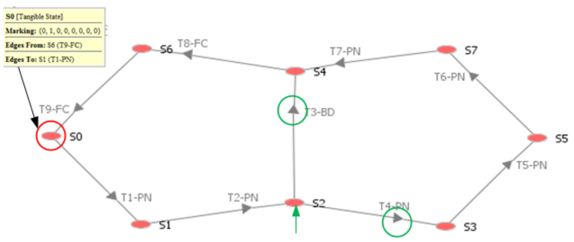

Figure 4: Main DPMS Reachability Graph with initial marking.

Through Main DPMS simulation, if verifies that does not exist Deadlock.However,checking a possible conflict highlighted with a black arrow on "S2" **BD** place output, between transitions "T_7-BD" and "T_8-PN", due to balancing result that evaluates two conditions: balanced FCU or unbalanced FCU. However, this "conflict", will not be controlled due to consider a random order in system simulation,when it executes balancing feeders analysis.

b) Invariants Analysis. Still looking for reachability graph, we note that all processes of system are sequential.However, BD process is the most critical because to determine the end of process, if it is found that FCU feeders are balanced, or the continuation of process otherwise, activating PV process.

This condition form, a specific place invariant: "PV" sub-process can not happen before "BD" sub-process.But also, we have the follow condition invariant: "BD", "PV","MN","SS" places cannot happen before "DP"sub-process. Thus, we have the follow condition:DP marking,BD marking,PV marking, MN marking and SS marking, should be less or equal to 1:

$$M(DP)+M(BD)+M(PV)+M(MN)+ M(SS)+\cdots \leq 1 \tag{4}$$

We also have the follow invariants: "Supervision Center"(SC),"Feeder Switching Control"(FC),"Consumption Data Record" (CDR) places cannot happen before "SS"sub-process. If any as a result of the process, no balanced FCU:

$$M(SS) + M(SC) + M(FC) + M(CDR) \leq 1 \tag{5}$$

In a similar situation, but starting from "BD" should also be considered the follow invariants: "Supervision Center"(SC),"Feeder Switching Control"(FC),"Consumption Data Record" (CDR) places cannot happen before "BD"sub-process. If any as a result of the process, FCU balanced:

$$M(BD) + M(SC) + M(FC) + M(CDR) \leq 1 \tag{6}$$

By P-Invariants result, we can verified that invariants indicates aboven, are true:

$$M(BD) + M(\text{Consumption Data Record}) + M(DP) + M(\text{Feeders Switching Control }) + M(MN) + M(PV) + M(SS) + M(\text{Supervision Center}) = 1 \tag{7}$$

The PN Invariants is shown in $2x9$ constant "T-Invariants" matrix depending on "T_{5-PN}","T_{6-PN}","T_{7-PN}","T_{8-FC}","T_{9-FC}", "T_{1-PN}","T_{2-PN}","T_{3-BD}","T_{4-PN}" transitions:

$$T_{Inv} = \begin{bmatrix} 1 & 1 & 1 & \cdots & 0 & 1 \\ 0 & 0 & 0 & \cdots & 1 & 0 \end{bmatrix} \begin{bmatrix} T_{5-PN} \\ T_{6-PN} \\ T_{7-PN} \\ T_{8-FC} \\ T_{9-FC} \\ \vdots \\ T_{4-PN} \end{bmatrix} \tag{8}$$

So, we can see, that The net is covered by positive T-Invariants, therefore it might be textbfbounded and **live**.

5.2 Hierarchical DPMS THPN validation

In Figure 5 it is shown the Hierarchical DPMS THPN simulation.Were performed 1500 "firings" with a period of 60 seconds between each, in order to have a complete operating in 1 minute. So, Were considered 60 FCU in SUSG, to be targets of balancing feeders analysis process. Thus, in "**CDR**" place there are electrical current and energy consumption of this 60 FCU.

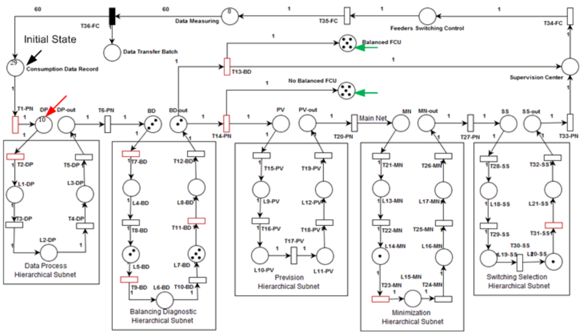

Figure 5: DPMS THPN Simulation.

During DPMS system simulation is verifying efficiently workflow, and there is not deadlock or conflicts (marked in green in Figure 6) like main PN, that needs regulatory control.

However, it is found some "**traps focus**" especially on "**BDout**" (in red), where are accumulated and consumed several tokens continuously, but it normalizes and adjusts over time.

It is, also found some "siphons focus" in "**No Balanced FCU**", where which are accumulated several tokens, but this is actually equal to "**No balanced FCU**" (in green): both are only process counters, to facilitate processing system count.

The DPMS THPN Reachability graph is shown in Figure 6. It represents the diagram of reachable states of the PN. Its initial state S_0 highlighted in red. If verifies that does not exist Deadlock, and that the PN it might be textbfbounded and **live**.

Looking for reachability graph, we note that all some specifics place invariant: "PV" sub-process can not happen before "BD" sub-process.But also, we have the follow condition invariant: "BD", "PV","MN","SS", "SC","FC", "Data Measuring (DM)", and "CDR", places cannot happen before "DP"sub-process. Thus, we have the follow condition:

$$M(DP)+M(BD)+M(PV)+M(MN)+ M(SS)+M(SC)+M(FC)+M(DM) +M(CDR)\leq 1 \tag{9}$$

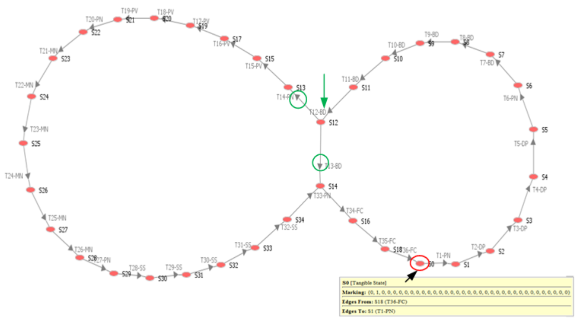

Figure 6: DPMS THPN Reachability Graph with initial marking and conflicts.

By P-Invariants result, we can verified that invariants indicates aboven, are true:

$$M(BD) + M(BD\text{-}out) + M(Consumption\ Data\ Record) + M(Data\ Measuring) + M(DP) + M(DP\text{-}out) + M(Feeders\ Switching\ Control\ ) + M(L10\text{-}PV) + M(L11\text{-}PV) + M(L12\text{-}PV) + M(L13\text{-}MN) + M(L14\text{-}MN) + M(L15\text{-}MN) + M(L16\text{-}MN) + M(L17\text{-}MN) + M(L18\text{-}SS) + M(L19\text{-}SS) + M(L1\text{-}DP) + M(L20\text{-}SS) + M(L21\text{-}SS) + M(L2\text{-}DP) + M(L3\text{-}DP) + M(L4\text{-}BD) + M(L5\text{-}BD) + M(L6\text{-}BD) + M(L7\text{-}BD) + M(L8\text{-}BD) + M(L9\text{-}PV) + M(MN) + M(MN\text{-}out) + M(PV) + M(PV\text{-}out) + M(SS) + M(SS\text{-}out) + M(Supervision\ Center) = 1 \tag{10}$$

6 Conclusion

A model Petri net, of load balancing process, called DPMS system to final consumption units in low voltage secondary grid, has been presented from which it is shown workflow formal validation. Having been used a timed hierarchical Petri net, to represent a dynamic abstraction of the operation flow of main and internal processes that form the DPMS system.Through the net synthesis,the reachability graph,invariant analysis and, workflow simulation, among others the vividness and limited network properties were checked. Verifying in summary efficiently operation of system without deadlocks and conflicts, that requested implementation of any regulatory control.Suggested future steps develop model DPMS system using timed hierarchical colored Petri nets,to further improve computational efficiency.

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