FLEXIBLE LV NETWORK INTERFACE FOR DYNAMIC POWER FLOW AND VOLTAGE CONTROL

Yin SUN
TU Eindhoven– the Netherlands
Y.Sun@tue.nl

Erik DE JONG, A. YANUSHKEVICH
DNV·GL – the Netherlands
Erik.deJong@dnvgl.com
Alexander.Yanushkevich@dnvgl.com

J.F.G COBBEN
TU Eindhoven – the Netherlands
J.F.G.Cobben@tue.nl

ABSTRACT

A future electrification scenario is envisaged where the energy demand from heat and transportation is supplied by electricity. In this scenario the current electricity network must adapt to prepare for high penetration levels of renewable energy sources and new energy applications, all connected to the MV and LV networks. This paper focuses on the associated LV network challenges, including roof-top Photovoltaic panels, Plug-in electric vehicles, Heat pumps that could significantly influence the future LV network design and operation. An innovative power electronics based concept called "Flexible LV Network Interface" is proposed. In this article, its capability to cope with the imminent challenge of voltage regulation is discussed. Time domain simulation results, performed in Powerfactory®, are presented and discussed as proof of control concept for "Flexible LV Network Interface".

1. INTRODUCTION

The future of electricity distribution systems will become increasingly interconnected with the demand for heat and transportation. Nowadays, two thirds of Europe's heat demand at residential and service sector buildings are met by the combustion of fossil fuels (petroleum, natural gas, etc.) [1]. However, in the future it is expected that Heat Pumps (HPs) will play an important role to meet the consumer heat demand thanks to its high "electricity to heat" efficiency. When it comes to energy demand for transportation, 73% of all oil imported by EU member states is consumed by the transport sector [2]. The European Commission forecasted that gradually replacing oil with cleaner transportation alternatives could significantly cut down its oil import and CO_2 emission. Adoption of cleaner mobility alternatives, such as Plug-in Electric Vehicles (PEVs), will lead to a low-carbon future transportation scenario. While the future energy demand from heat and transportation sector is expected to be supplied by electricity, the successful transition towards a sustainable, reliable and affordable energy future is dependent on the clean energy production, such as renewables. A future electrification scenario is therefore envisaged in the LV network where renewable energy is produced by roof-top Photovoltaic (PV) panels, and consumer heat/transportation demand is satisfied by HPs and PEVs.

2. PROBLEM DEFINITION

Nowadays LV networks are designed to meet both the regulatory ±10% voltage limits [3] as well as the transformer/cable thermal rating limits, taking into account consumer peak load, diversity factor, and expected future load growth. MV/LV transformers are typically equipped with off-load tap changers, with some exceptions where on-load tap changers are utilized for additional voltage regulation to cope with peak load voltage drops in time intervals of 15 minutes.
In order to facilitate high electricity demand from heat and transportation fed by renewable energy generation, future LV networks should be built/enhanced with a high level of flexibility, controllability and reliability to maximize the integration of sustainable/energy efficient technologies. To understand the impacts of high penetration level of PEVs, PVs, and HPs on LV network, the following paragraphs present the findings from literature study. The research question is summarized in the end.

Impact of PEV charging

Electric Vehicle charging represents a heavy energy demand challenge for the network. [4]-[5] discusses component overloading and the voltage regulation challenges introduced by EV charging when its penetration level in the current LV network infrastructure becomes high. Firstly, EV charging could significantly affect the voltage profile along the LV feeder and result in unacceptable voltage deviation beyond the regulatory voltage limit. Secondly, according to [4] a high EV in-take rate (71%) in LV network could cause 50% MV/LV supply transformers and 13% supply cables overload. Although temporary component overload may only slightly affect the life expectancy of the concerned assets, a continuous heavy overload could eventually lead to network outages and irreversible component damage.

Impact of PV energy production

Because of the roof-top PV, the traditional passive LV distribution network has become active. In some extreme situations, the PV energy production can greatly exceed the local consumption causing voltage increase at the supply feeder end due to reverse power flow towards the MV/LV substation [6]. A neighbourhood with a high penetration level of roof-top PV will create a voltage regulation challenge. Furthermore, the PV energy production is dependent on the panel temperature and solar irradiance. In contrast to the slow variation in temperature, the solar irradiance can fluctuate within seconds. In this case continuous voltage control will be essential to maintain the voltage along the LV feeder within regulatory limits at all times.

Impact of HP operation

Heat pumps have been gaining attention due to its high electricity-to-heat conversion efficiency. Despite all the benefits heat pumps can bring into the domestic heat market, its operation is dependent on the quality of the electricity supply. A heat pump largely behaves the same as an air conditioner in the event of a voltage dip. The compressor motor will quickly stall if the supply voltage goes below 0.6pu for more than 5 cycles [7][8], and the compressor motor will continuously draw high current due to high pressure in the compressor. Following the supply voltage recovery, the compressor motor will remain stalled until the thermal cut-off relay disconnects the equipment from the network.

Research Question

Considering the abovementioned challenges, the answer to the following research question is essential to prepare the current LV network infrastructure for the years to come:

"What technology will enable LV network to support the envisioned future electrification scenario with high degree of flexibility and controllability?"

3. FLEXIBLE LV NETWORK INTERFACE CONCEPT

The on-load tap changer of a MV/LV transformer can be equipped to offer voltage regulation at LV feeders with high penetration level of PVs, PEVs, and HPs. Depending on the voltage measurement location and the transformer on-load tap changer range, the voltage control is discrete and sometimes an optimized voltage and power flow cannot be achieved to satisfy the regulatory voltage requirement for all LV feeder connections. To cope with the envisaged future development in the LV network, where a high penetration of distinctive technologies (PVs, PEVs, and HPs etc.) appear in the LV feeders, a back-to-back converter concept, shown in Figure 1, is proposed to offer not only continuous voltage control capability but also additional control functions. The concept itself provides LV and MV network decoupling, on the one hand it isolates the LV network from the MV network background harmonic distortion, and on the other hand the LV network can be supplied by DC storage device during MV network disturbances. In addition to active power regulation, the grid side converter can regulate the reactive power output and provide active filtering function on demand. Besides continuous voltage regulation capability, feeder side converter also possess frequency regulation capability, which is essential for controllable PV production and EV charging [9]. When resonance occurs in the LV network, feeder side converter can provide active damping and stable the LV network. The back-to-back power electronics concept (Figure 1 below) will be referred to as "LV Network Flexible Interface Concept" in the rest of this article.

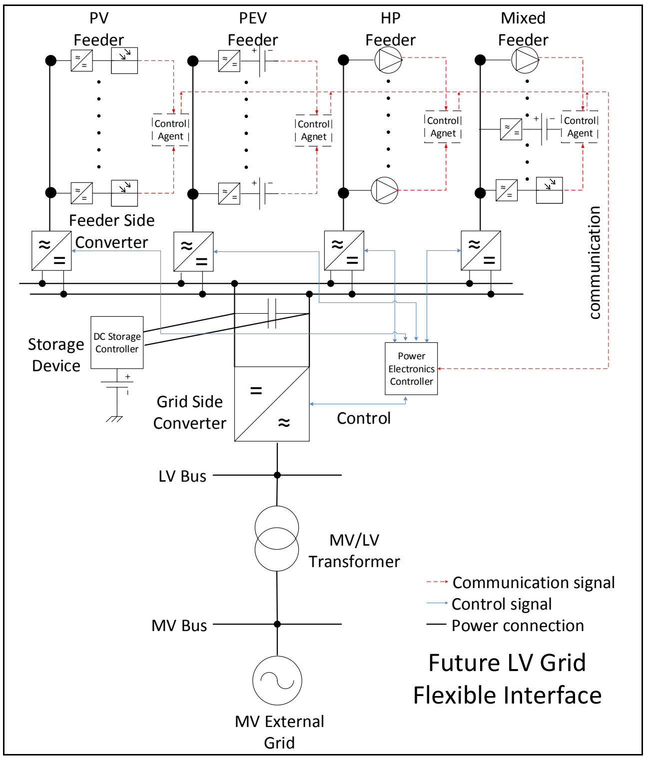

Figure 1 Future LV grid flexible interface concept

Grid side converter: The grid side converter (Figure 1) serves as the interface between the external AC network and the DC bus. The dq0 frame current control strategy is adopted to independently control the direct axis current and the quadrature axis current when the network side converter is perfectly synchronized to the AC network voltage, via phase-locked-loop (PLL). In addition to the converter inner current control loops, two outer loops are necessary (Figure 2) to maintain a stable DC bus voltage (V_{dc}) as well as adequate reactive power exchange (Q) with the AC network.

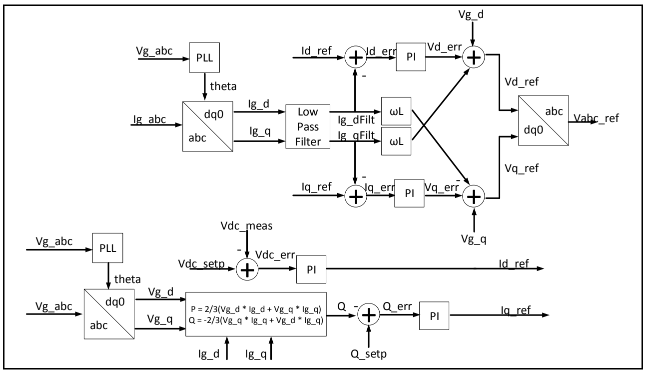

Figure 2 Network side converter control block diagram

Feeder side converter: The feeder side converter (Figure 1) is responsible for the LV network voltage and frequency. Frequency control loop manages supply voltage frequency at 50Hz constant. During transformer/cable overload, controllable PV production and EV charging can be achieved by frequency droop control concept. The PWM modulation index is dynamically controlled to maintain the feeder AC voltage at 400V (Figure 3).

To ensure a healthy voltage profile along the LV supply feeder, TCP/IP protocol based communication is proposed to regulate voltage at remote feeder end terminal. The extra voltage summation point V_{agent} is to adjust the feeder voltage set-point when the feeder terminal end voltage violates pre-set operational limit.

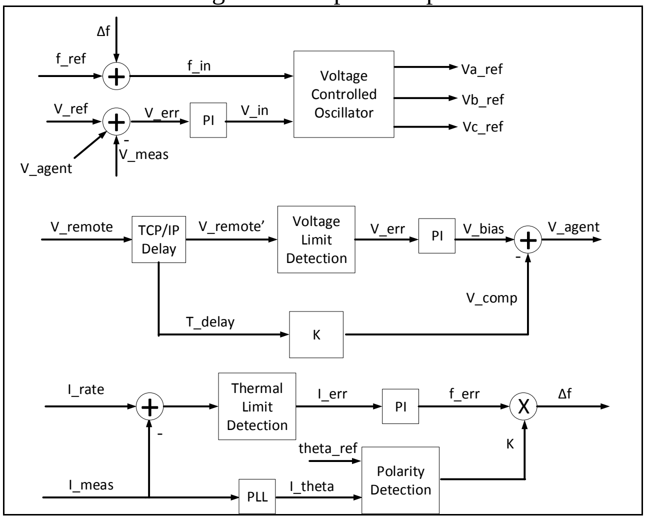

Figure 3 Feeder side converter control block diagram

DC storage and AC fault ride through: The energy storage device (Figure 1) rapidly charges the DC bus during external network fault conditions as well as during abnormal supply conditions. The storage device here has been chosen to cope with a short-time disturbance and compensate any temporary external AC supply energy shortage.

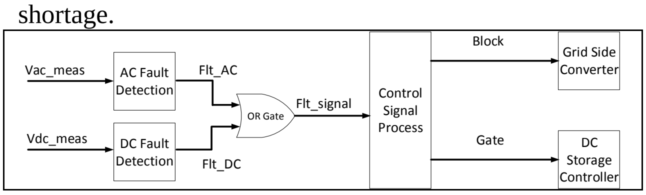

Figure 4 DC storage and AC fault control block diagram

Figure 4 shows the simplified control block diagram of the DC storage and AC network converter fault ride through control strategy. Upon fault detection, network side converter will receive the block signal and DC storage device starts conducting. Once fault condition is resolved, network side converter will synchronize back to the external network, and DC storage device will receive the gate close signal and stop conducting.

4. CASE STUDY SIMULATION RESULTS

In order to verify the proposed "LV Network Flexible Interface Concept", a segment of the Dutch LV network is used and modified to represent the envisaged future electrification scenario, including the high penetration level of PVs, PEVs, and HPs connected to the LV network.

In this section, the original Dutch LV network is introduced first. Then the modifications made to the original Dutch LV network are presented. In order to demonstrate the feasibility of the "LV Network Flexible Interface" concept, time domain simulations have been performed using Powerfactory®. The following events were investigated:

1) External AC network three-phase fault
2) Multiple heat pumps simultaneous start-up
3) Irradiance increase and PV production variation
4) Simultaneous PEVs charging

The LV network in the suburb *Nieuwe Tijningen* has in total 383 customers supplied via 7 feeders. 4 out of 7 feeders are modelled and enhanced with the envisioned future electrification scenario features, represented by additional PVs, PEVs and HPs connected at the customer terminals.

Items	Feeder 1	Feeder 2	Feeder 3	Feeder 4
Customers	27	24	52	74
No. of PVs	9	0	27	0
No. of PEVs	10	0	0	38
No. of HPs	8	24	0	0

Table 1 LV network summary

Table 1 and Table 2 show the number of customers connected at each individual feeder, the respective number of PVs, PEVs, and HPs and the main electrical parameters. Feeder 4 resembles a high PEV penetration, while feeder 3 resembles a high PV penetration. Feeder 2 is characterized with high heat pump penetration, while feeder 1 resembles a mix.

	Network Converter	Feeder Converter
Voltage	400V	400V
Rating	1000kVA	200kVA
Modulation	Sinusoidal PMW	SinusoidalPMW
Control	Vdc, Q	Vfac, f
Undc	700V	
Cdc	5000μF	
	MV/LV Transformer	
Vector Group	Dyn11	
HV/LV	10/0.4 kV	
Uk	3.75%	
Copper Losses	5.75kW	
Thermal Rating	630kVA	
Frequency	50Hz	
	External MV Network	
SC Power	100MVA	
R/X Ratio	0.6	

Table 2 LV flexible network interface main parameters

The PV is dynamically modelled with maximum 5kW output. The PV converter controls the active power output at unity power factor by sinusoidal PWM modulation. The PV array's DC output is modelled as a function of solar irradiance only. The PEV is dynamically modelled with maximum 3kW power demand. The PEV converter controls the active power input at unity power factor by sinusoidal PWM modulation. The HP is dynamically modelled with directly coupled AC motor of 2.2kW, 96% efficiency, 0.85 power factor at nominal speed. The compressor driven load characteristic is also modelled and motor starting time is 12 second with 7.2pu locked rotor current. Customer household load is modelled as impedance type with 0.8kW, 0.98 power factor.

Results – External AC fault ride through (FRT)

An external AC disturbance is simulated (Figure 5) as three-phase fault (0.01Ω) at the MV network terminal at 100ms; the fault clearing time is assumed to be 100ms and the network converter is resynchronized at 220ms.

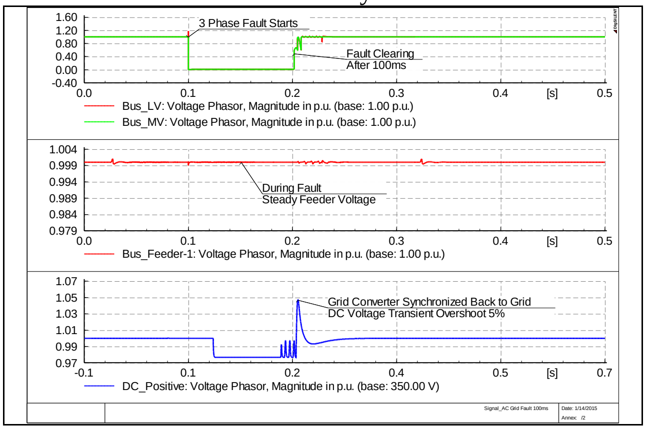

Figure 5 Simulation results - MV grid fault

From top to bottom (Figure 5): plot 1 is the voltage measured at the external AC network MV and LV side. Plot 2 is the voltage measured at the LV feeder 1 supply bay, it shows that the voltage supply at the LV feeder supply is not disturbed thanks to the DC energy storage device. Plot 3 shows that the DC bus voltage is very well maintained throughout the disturbance event. Less than 5% overshoot is observed when the network side converter is resynchronized at 220ms.

Results – Dynamic feeder voltage regulation

The dynamic LV feeder continuous voltage and power flow regulation capability is demonstrated in Figure 6-Figure 9.

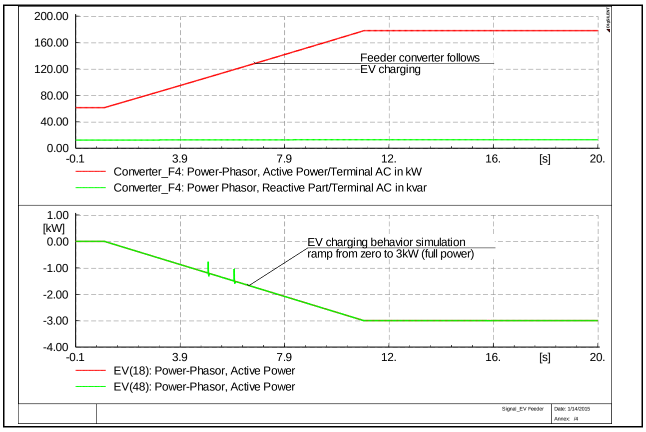

Figure 6 Simulation results - Feeder 4 with PEVs

Figure 6 shows that all the PEVs in feeder 4 start charging at second 1. It is assumed that PEVs will ramp from 0kW to 3kW (nominal charging power) in 10 seconds. The results show that the LV network feeder converter is able to manage the power flow variation introduced by the PEVs charging during start-up and the LV feeder AC voltage remains tightly controlled to 1pu (Figure 9).

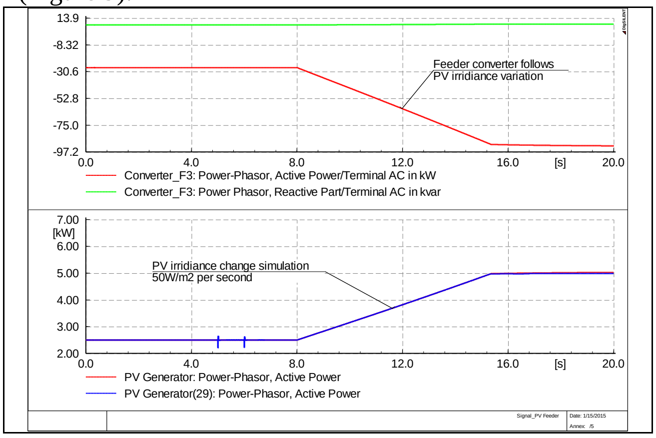

Figure 7 Simulation results - Feeder 3 with PVs

Figure 7 shows that the solar irradiance associated with feeder 3 rises from 400W/m^2 (around 2.5kW output) to approximately 800W/m^2 (around 5kW output) with a ramp rate of 50W/m^2 per second. The results show that the LV network feeder converter could manage the sudden solar irradiance variation and the associated PV power production change while keeping the LV feeder voltage at 1pu (Figure 9).

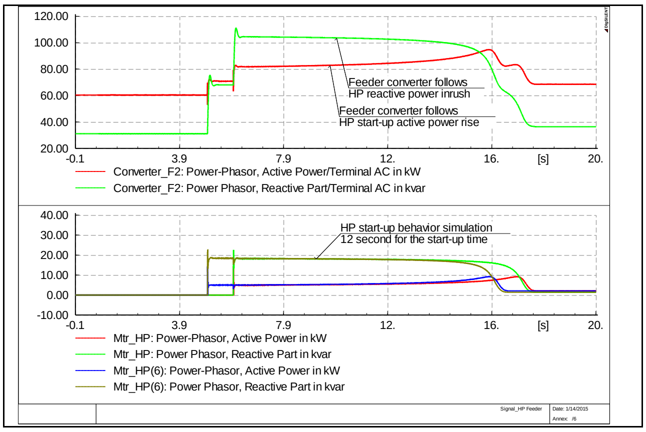

Figure 8 Simulation results - Feeder 2 with HP

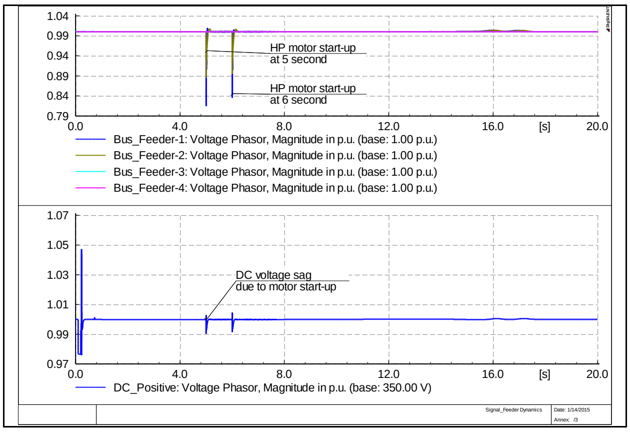

Figure 9 Simulation results - Feeder side voltage regulatio

Figure 8 shows that two HPs in feeder 2 start up at second 5 while another two HPs start up at second 6. The results show that the motor reactive inrush current could disrupt the voltage at the LV network feeder and cause it to plummet below 0.9pu for less than 20ms. Thanks to the rapid control of the LV network feeder converter, the feeder voltage will quickly recover and maintain it at 1pu during the remainder of the motor start-up period (Figure 9).

5. CONCLUSIONS

This article proposes an innovative "LV Network Flexible Interface Concept" to support the envisioned future electrification scenario in the LV network, where very high penetration levels of PVs, EVs and HPs are foreseen. The control strategy of the network side converter, the feeder side converter, and the DC storage controller are developed and implemented in Powerfactory®.

In order to prove the feasibility of proposed control strategy and proclaimed benefits introduced by "LV Network Flexible Interface", a segment of the Dutch LV distribution network has been selected and modified to represent the envisioned future electrification scenario with high penetration level of PVs, PEVs and HPs. Simulation results from case study not only depict FRT capability during external AC network faults but also demonstrate continuous voltage regulation capability at individual supply feeders taking into account typical dynamic behaviours of PVs, PEVs, and HPs.

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