Transformer Overloading Control by Controlling the Operational-Modes of High-Power Converters

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***Abstract*—. With the increasing penetration of renewable sources and energy storage, high-power converters including voltage source converters (VSCs) and dc/dc converters are getting fair occupation into power grid. These high-power converters could be used to control the transformer's overloading by controlling their operational modes. For a VSC, operational modes include rectification and inversion operation, and for a dc/dc converter, operational modes include buck and boost operation. These operational modes are administrated by a proposed algorithm, which senses the power handled by distribution transformer and keeps it within a designated threshold. The algorithm carries out all this by controlling the power flow from/to grid to/from battery storage. All power converters operate in a closed-loop where reference is tracked by using PI-control. In this paper, the authors have improved the performance of power converters by introducing fuzzy-control. A simulation model including grid, transformer, AC bus, dynamic load, VSC, dc/dc converter and battery-storage has been developed in MATLAB/Simulink environment. A test case of overloading of transformer is simulated and performance of PI-control and fuzzy-control for power converters is evaluated. It is seen that fuzzy-control gives a better performance than PI-control.**

Keywords—transformer, VSC, DC/DC converter, fuzzy-control, PI-control, overloading, operational-modes

I. INTRODUCTION

The integration of renewable energy sources (RES) directly as distributed energy resources (DERs) has restructured the conventional power grid. As a result, the supply of local load by local DERs has evolved the concept of a microgrid [1-2]. The DERs offer benefits like low operational costs and low emissions. However, due to the intermittent nature of the DERs like wind and solar, a fluctuating power is produced [2-3]. In grid-connected mode, the power balance is assured by utility grid. During islanding, additional resources like diesel generators or energy storage are required for power balancing. However, some drawbacks like increased capital costs, CO_2 emissions and engine's sound, are attached to these schemes [4]. Nevertheless, the response time of the battery-storage is much faster than diesel generators [5], and battery-storage also offer the benefit of being a controllable load, which means that power flow towards battery storage could be controlled. This feature of battery-storage could be used in controlling the transformer's overloading. When normal load is connected in parallel to battery-storage, the current division towards battery-storage could be controlled to keep transformer's loading within designated threshold. In case of increase in normal load, the current towards battery-storage could also be reversed to save transformer from overloading. This control is achieved by controlling the operational-modes of high-power converters including voltage source converters (VSCs) and dc/dc converters. These power converters operate in a closed-loop, where reference power/voltage signal is tracked by using PI-control or some other compensation method.

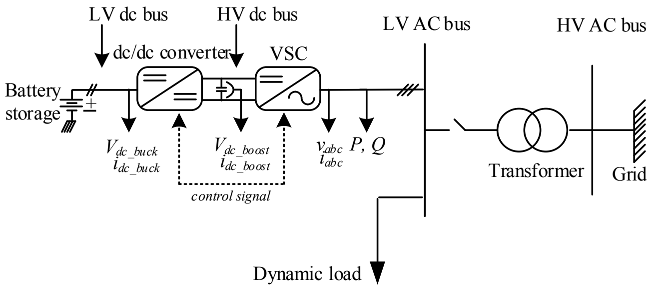

Fig. 1. Simplified model of radial distributor

In published literature different approaches and techniques have been investigated. The authors in [6], have investigated transformer's overloading due to PV power injection. However, only grid-connected mode is considered and PI-control is used. The authors in [7], have investigated overloading of distribution transformer and cables. They proposed a dynamic voltage regulator (DVR) between distribution transformer and load, and used PI-control for DVR. The authors in [8], have investigated the overloading of neutral conductor and distribution transformer. They proposed a PI-controlled smart VSC, which operates with PV, and regulates AC side voltage and minimizes transformer's overloading. The authors in [9], have investigated the overloading of a distribution system and proposed a distributed algorithm which involves PI-control. However, only grid-connected mode is discussed. The authors in [10], have investigated transformer's degradation. They proposed a two-tier energy compensation framework in the form of a convex optimization problem. However, only battery-storage's charging/discharging has been discussed and no control is

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used. The authors in [11], have investigated the voltage swell problem at distribution transformer's level. They proposed a dynamic capacity distribution (DCD) method with an active unbalance compensator. Only PI-control is used.

In this paper, the authors have investigated the overloading of distribution transformer due to dynamic load. Both grid-connected and islanding modes are considered. The simplified model of a radial distributor is taken into consideration, which is fed by grid via a distribution transformer. At the AC bus, both dynamic load and battery-storage are connected. Dynamic load has a direct integration to AC bus. However, battery-storage is integrated through a VSC and a dc/dc converter. During the charging operation of battery-storage, VSC operates as a rectifier and dc/dc converter operates as a buck converter. In this operation the power flow through battery is controlled by controlling the current of buck converter and a stiff voltage at dc bus is maintained by VSC. During the discharging operation of battery-storage, VSC operates as an inverter and dc/dc converter operates as a boost converter. In this operation the power flow towards AC bus is controlled by controlling the current of inverter and a stiff voltage at dc bus is maintained by boost converter. Both VSC and dc/dc converter regulate/track the reference signal by using PI-control. In the paper, the authors have improved the performance of these high-power converters by introducing a fuzzy-control, which regulates/tracks the reference signal of power or voltage depending upon operational mode.

Rest of the paper is organized as follows: Section II explains the simplified model of a radial distributor. Section III explains PI-control and fuzzy-control for controlling of transformer's overloading. Section IV presents the proposed algorithm for controlling of transformer's overloading. Section V discusses the test case and results. Section VI draws the conclusions.

II. SIMPLIFIED MODEL OF RADIAL DISTRIBUTOR

Figure 1 shows the simplified model of a radial distributor [12]. It is connected to grid via a distribution transformer at low voltage (LV) AC bus, whose overloading is to be controlled. The transformer is connected to grid at high voltage (HV) AC bus. A dynamic load is directly connected at LV AC bus. Battery-storage is connected at LV AC bus via a VSC and a dc/dc converter. A high voltage (HV) dc is maintained at HV dc bus either by VSC or dc/dc converter depending upon operational mode. Similarly, a low voltage (LV) dc is maintained at LV dc bus by dc/dc converter in buck operation or battery-storage. Table 1 shows detailed parameters of simplified model of radial distributor.

III. CONTROL DESIGN

The control design has two levels. The first level is overloading control of distribution transformer. Figure 2 shows flow chart of algorithm for overloading control. It starts with sensing of power handled by transformer at LV AC bus. If the transformer's kVA rating is within designated threshold, sensing is continued. If overloading is detected, immediately power flow towards battery-storage is restricted. It is done by controlling the flow of current of dc/dc converter (buck operation) towards battery-storage. Overloading is sensed again, if still not under control, current is forced to flow from battery-storage towards LV AC bus. It is done by using dc/dc converter in boost operation and VSC as an inverter.

The second level is control of VSC and dc/dc converter for respective operational modes depending upon power flow requirement. Figure 3 [12] and figure 4 [17] show the control steps for grid-connected and islanding modes, respectively. For VSC in grid-connected mode, phase (ϑ) is sensed from the grid by using a phase lock loop (PLL), as shown in figure 3 (a). However, for islanding mode it is self-generated, as shown in figure 4 (a). VSC's control uses park transformation to convert three phase AC voltages and currents at LV AC bus into their direct and quadrature components, which are further used in outer and inner loops for control signal generation. Figure 3 (b-c) and figure 4 (b-d) show these steps in detail. In grid-connected mode dc/dc converter is used as a buck converter. It controls the power flow towards battery-storage by controlling its current, as shown in figure 3 (d). However, it can also be used to maintain a stiff dc voltage at LV dc bus in case of totally discharged battery-storage. It can used as boost converter in both grid-connected as well as islanding modes, as shown in figure 3 (e) and 4 (a). It is used to maintain a stiff dc voltage at HV dc bus in both modes. Whereas, VSC controls AC current towards LV AC bus in grid-connected mode and AC voltage at LV AC bus during islanding.

Both of VSC and dc/dc converters use PI-control or fuzzy-control (PI/fuzzy control) to track reference of voltage or power. Equations (1) to (3) are transfer functions of dc/dc converter [16]. Similarly, equations (4) to (8) are for VSC [15]. Table 2 and Table 3 show fuzzy rules for VSC and dc/dc converters [13,14].

TABLE I. MODEL PARAMETERS

Sr. No.	Component	Parameter/Rating
1	Transformer (11kV/400V)	104kVA
2	AC bus Voltage (line-line)	400V
3	VSC	100kVA
4	dc/dc converter	100kW
5	Dynamic load	36-126KW
6	Line resistance	2mΩ
7	Line reactance	2mH
8	Line capacitance	102.3μF
9	Battery storage	700V
10	dc side filter (765V)	4400μF
11	dc/dc converter inductance	6.2mH
12	dc/dc converter capacitance	450μF
13	VSC switching frequency	10kHz
14	dc/dc converter switching frequency	5kHz

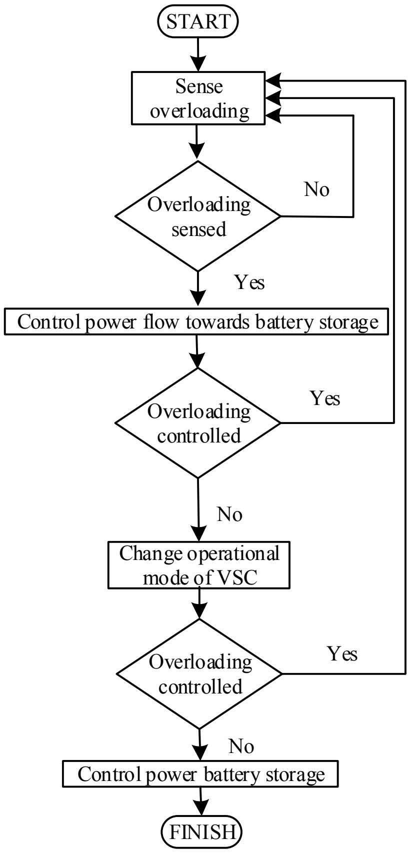


Fig. 2. Flow chart of algorithm for overloading control

$$\frac{Vdc\_buck}{d}=\frac{Vin}{LC}\cdot\frac{1}{s^2+\frac{s}{RC}+\frac{1}{LC}} \tag{1}$$

$$\frac{Idc\_buck}{d}=\frac{Vin}{L}\cdot\frac{s+\frac{1}{RC}}{s^2+\frac{s}{RC}+\frac{1}{LC}} \tag{2}$$

$$\frac{Vdc\_boost}{d}=\frac{Vin}{RC(1-D)^2}\cdot\frac{\frac{R(1-D)^2}{L}-s}{s^2+\frac{s}{RC}+\frac{(1-D)^2}{LC}} \tag{3}$$

$$\frac{d}{dt}Id=\frac{-R}{L}Id+wIq-\frac{1}{L}vd+\frac{1}{L}Ed \tag{4}$$

$$\frac{d}{dt}Iq=\frac{-R}{L}Iq-wId-\frac{1}{L}vq+\frac{1}{L}Eq \tag{5}$$

$$\frac{d}{dt}vdc=\frac{-1}{RdcCdc}Vdc+\frac{3}{2Cdc}MdId+\frac{3}{2Cdc}MqIq \tag{6}$$

$$[V]=\frac{1}{2}[M]Vdc \tag{7}$$

$$Idc=\frac{1}{2}[M]^T[I] \tag{8}$$

TABLE II. FUZZY RULES FOR VSC

Δe/e	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NB	NS	NS	Z
NM	NB	NB	NB	NM	NS	Z	PS
NS	NB	NB	NM	NS	Z	PS	PM
Z	NB	NM	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PM	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PB	Z	PS	PM	PB	PB	PB	PB

TABLE III. FUZZY RULES FOR DC/DC CONVERTER

Δe/e	**NB**	**NM**	**NS**	**Z**	**PS**	**PM**	**PB**
NB	NB	NB	NB	NM	NM	NS	Z
NM	NB	NM	NM	NS	NS	Z	PS
NS	NB	NM	NS	NS	Z	PS	PM
Z	NM	NS	NS	Z	PS	PM	PB
PS	NM	NS	Z	PS	PS	PM	PB
PM	NS	Z	PS	PS	PB	PB	PB
PB	Z	PS	PM	PM	PB	PB	PB

Where, NB is Negative big, NM is Negative Medium, NS is Negative small, Z is zero, PS is Positive small, PM is Positive medium and PB is Positive big.

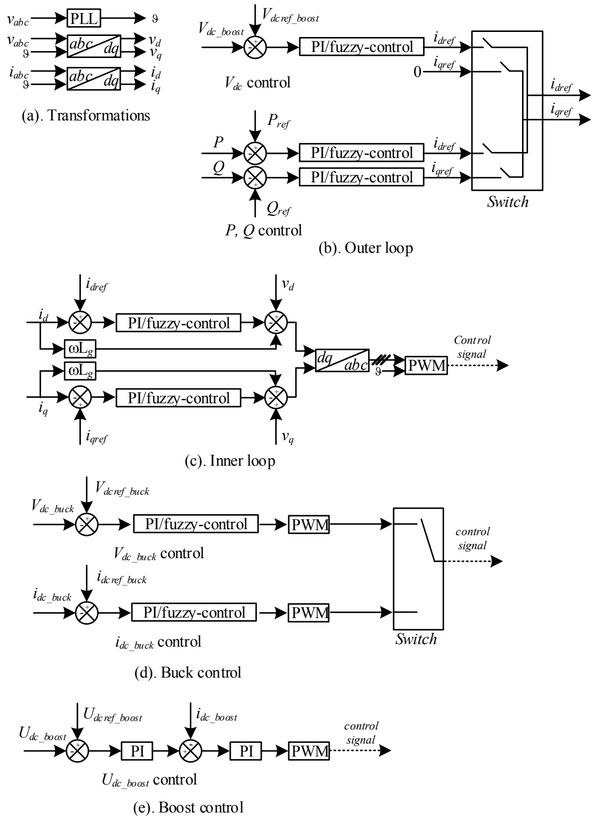


Fig. 3. Control of VSC and dc/dc converter in grid-connected mode

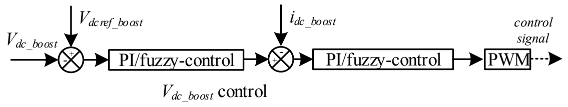
IV. TEST CASE AND RESULTS

A test case with simplified model of radial distributor is simulated. Total simulation time is set to be 0.3 sec. Figure 5 (a) and figure 5 (b) show load power with step changes and respective grid power fulfilling load demand, whereas Table 4 summarizes respective values. It can be seen that initial load is 36kW. 1st step change of 72kW in load occurs at 0.07 seconds and 2nd step change of 120kW in load occurs at 0.14 seconds. At 0.2 seconds islanding occurs and load is reduced to 40kW, however it goes to zero.

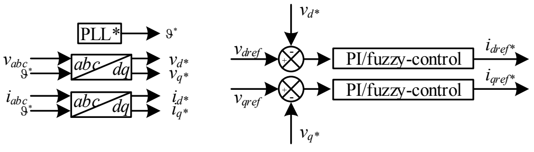
TABLE IV. POWERS AT LV AC BUS

Power (kW)	Constant load (kW)	1st step change in load (kW)	2nd step change in load (kW)	Islanding (kW)
P_{load}	36	72	120	40
P_{grid}	104	104	104	0
$P_{battery\text{-}storage}$	68	32	-16	-40

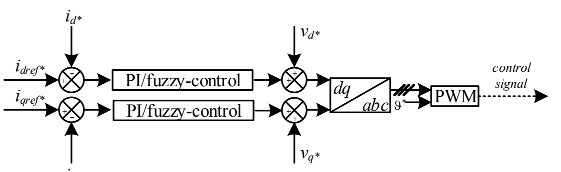
Figure 6 (a), (b) and (c) show load power, grid power and battery-storage power with overloading control. It can be seen from figure 6 (b) that during step changes and islanding proposed overloading control with fuzzy-control gives a better performance than PI-control in terms of overshoot, undershoot, rise time, settling time, steady state error and time to steady state. Similarly figure 6 (c) shows battery-storage's power to control the overloading during step changes and islanding. It is obvious that in this case fuzzy-control outperforms PI-control as well. Figure 7 shows dc voltage at HV dc bus and it is again clear that fuzzy-control gives a better and stiffer voltage than PI-control. Figure 8 shows phase A of AC voltage and Current at LV AC bus. Again fuzzy-control gives a less deviated and less overshot voltage than PI-control. Tables 5 to 10 show this comparison in numeric values. Table 11 shows total harmonic distortion (THD) of v_{abc} at LV AC bus during both grid-connected and islanded modes with both PI-control and fuzzy-control. It can be seen that fuzzy-control has less THD as compared to PI-control.



(a). Boost control



(b). Transformations (c). Outer loop



(d). Inner loop

Fig. 4. Control of VSC and dc/dc converter in islanding mode

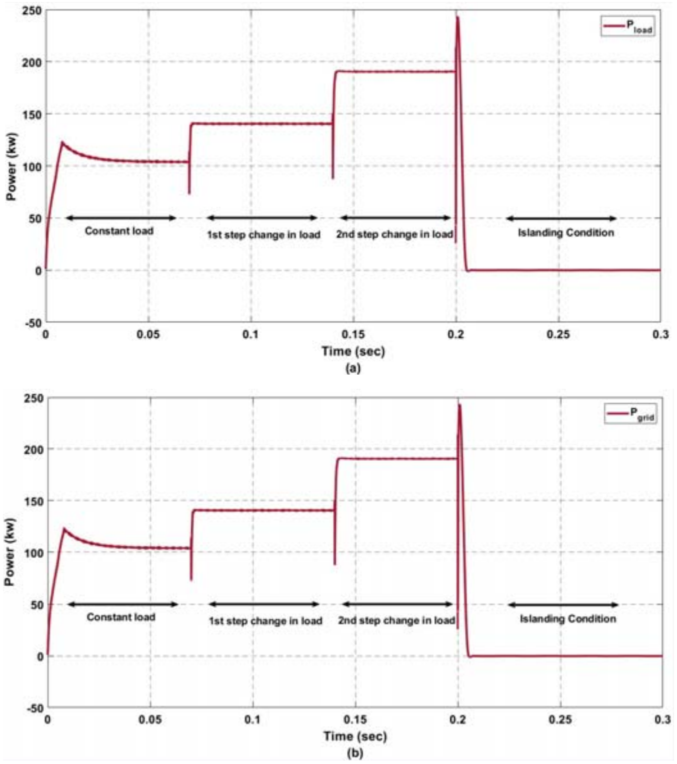


Fig. 5. Load and grid power without overloading control

TABLE V. VOLTAGE AT LV DC BUS WITH PI-CONTROL

Indicator	Constant load (sec)	1st step change in load (sec)	2nd step change in load (sec)	Islanding (sec)
Overshoot	0	0	0	0
Undershoot	0	0.0715	0.15	0.206
Rise time	0.006	0.071	0.147	0.202
Settling time	0.0015	0.072	0.152	0.212
Steady state error	0	0.6%	3.3%	0
Time to steady state	0.0016	0.073	0.153	0.23

TABLE VI. VOLTAGE AT LV DC BUS WITH FUZZY-CONTROL

Indicator	Constant load (kW)	1st step change in load (kW)	2nd step change in load (kW)	Islanding (kW)
Overshoot	0	0	0	0.204
Undershoot	0	0.0705	0.142	0
Rise time	0.006	0.0702	0.141	0.201
Settling time	0.0015	0.0715	0.145	0.21
Steady state error	0	0.4%	1%	0
Time to steady state	0.0015	0.0715	0.145	0.22

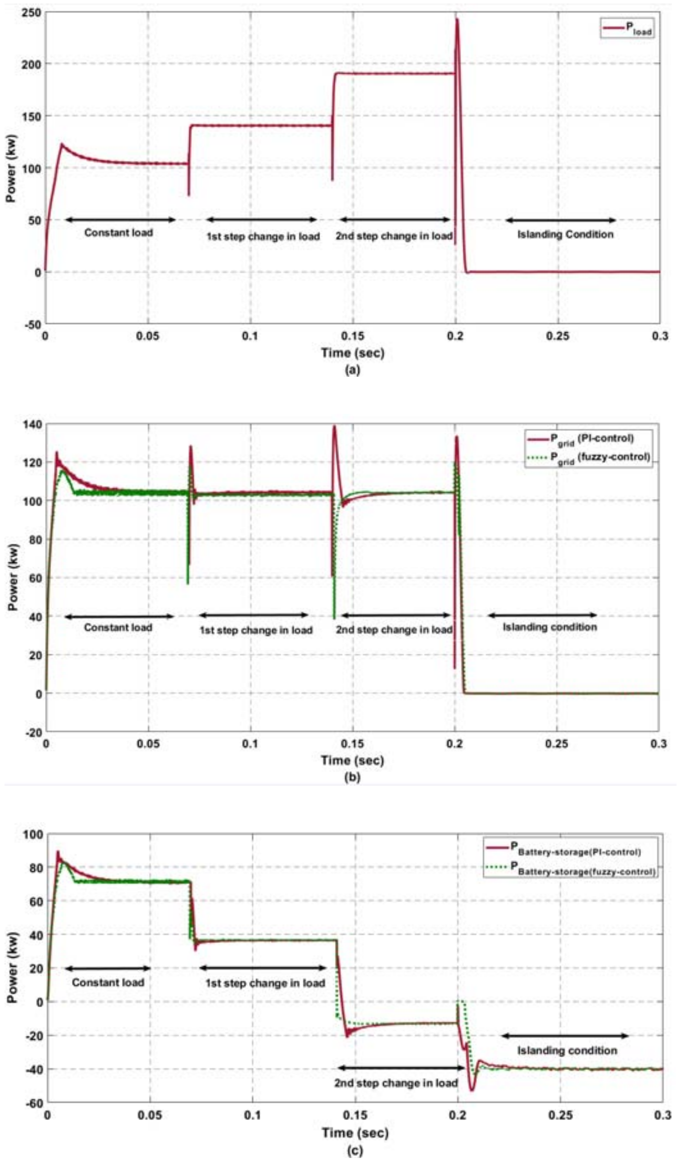


Fig. 6. Load, grid and battery storage power with overloading control

TABLE VII. PGRID AT LV AC BUS WITH PI-CONTROL

Indicator	**Constant load (kW)**	**1st step change in load (kW)**	**2nd step change in load (kW)**	**Islanding (kW)**
Overshoot	0.0045	0.0707	0.141	0.201
Undershoot	0	0	0	0.202
Rise time	0.004	0.0704	0.1405	0.2006
Settling time	0.02	0.074	0.144	0.204
Steady state error	0	0	0	0
Time to steady state	0.04	0.075	0.155	0.2045

TABLE VIII. PGRID AT LV AC BUS WITH FUZZY-CONTROL

Indicator	**Constant load (kW)**	**1st step change in load (kW)**	**2nd step change in load (kW)**	**Islanding (kW)**
Overshoot	0.004	0.0704	0	0.2005
Undershoot	0	0	0.1405	0
Rise time	0.003	0.0702	0.1402	0.2002
Settling time	0.01	0.0703	0.141	0.203
Steady state error	0	0	0	0
Time to steady state	0.02	0.072	0.152	0.204

TABLE IX. PLOAD AT LV AC BUS WITH PI-CONTROL

Indicator	**Constant load (kW)**	**1st step change in load (kW)**	**2nd step change in load (kW)**	**Islanding (kW)**
Overshoot	0.005	0	0	0.208
Undershhoot	0	0.0703	0.145	0.214
Rise time	0.0045	0.0701	0.144	0.206
Settling time	0.022	0.0735	0.151	0.218
Steady state error	0	0	0	0
Time to steady state	0.03	0.076	0.153	0.224

TABLE X. PLOAD AT LV AC BUS WITH FUZZY-CONTROL

Indicator	**Constant load (kW)**	**1st step change in load (kW)**	**2nd step change in load (kW)**	**Islanding (kW)**
Overshoot	0.004	0	0	0
Undershoot	0	0.0701	0.143	0.21
Rise time	0.004	0.07	0.141	0.208
Settling time	0.01	0.0715	0.15	0.212
Steady state error	0	0	0	0
Time to steady state	0.015	0.073	0.151	0.215

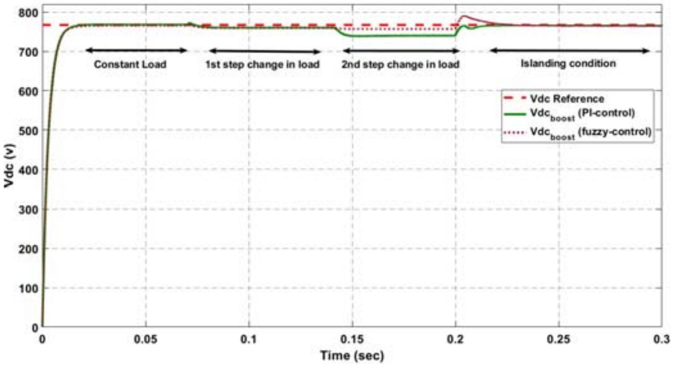


Fig. 7. dc voltage a HV dc bus

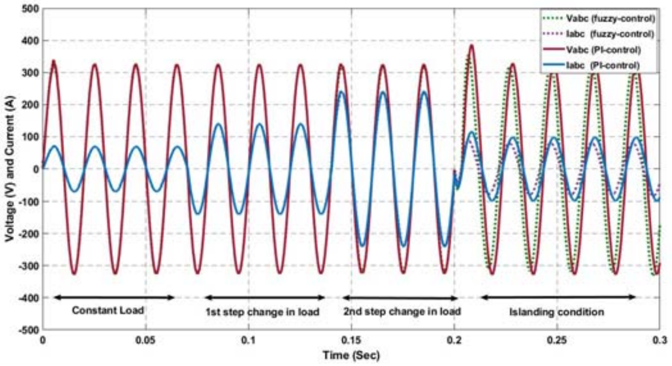


Fig. 8. AC voltage at LV AC bus

TABLE XI. THD OF VOLTAGES AT LV AC BUS

v_{abc} **@ LV AC bus**	**THD**
Grid-connected mode (fuzzy-control)	0.9%
Grid-connected mode (PI-control)	2.22%
Islanding mode (fuzzy-control)	0.78%
Islanding mode (PI-control)	1.24%

V. CONCLUSIONS

The authors have proposed to control transformer's overloading by controlling the operational modes of high-power converters including VSC and dc/dc converters. These operational modes were administrated by a proposed algorithm, which senses the power handled by distribution transformer and keeps it within a designated threshold. It is done by controlling the power flow from/to grid to/from battery-storage. Furthermore, the authors have improved the performance of power converters by introducing fuzzy-control. The results of test case of overloading of transformer compare performance of PI-control and fuzzy-control for high-power converters. It is obvious from results that fuzzy-control gives a better performance than PI-control in terms of overshoot, undershoot, rise time, settling time, steady state error and time to steady state.

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