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Four-leg inverters for unbalanced grid feed-in from Renewable energy sources

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Motivation

Standalone systems cannot be assumed as balanced three phase networks. A microgrid has a limited energy pool which is distributed unevenly over the loads. A microgrid controller needs to mitigate network imbalances on an active basis. Unbalanced and non-linear loads (electronic devices) require inverters to be able to track unbalanced current references. The work seeks to combine a robust current control strategy with a highly unbalanced three-phase active power injection at point of common coupling (PCC) while staying in the a-b-c domain with less computational effort.

Limitation

Topology For Unbalanced Loads

- Split DC-link, Delta/Star – current harmonics & low utilization of DC voltage, Expensive to add a transformer.

Controller [2]-[6]

- PID controllers with PWM – complicated implementation, computationally intensive.

Filter Model

LCL filter is approximated as L – RMS error in grid current tracking, active power injection is not controlled.

Solution

Four leg [1]

Active control of neutral voltage, high DC voltage utilization.

Finite set predictive controller [7]-[8]

Easy implementation, computationally simple, three phases are completely decoupled, works in a-b-c domain.

Filter current feedback with active power loop

Controls active power strictly even after approximation.

Implementation

State Space Definition Of Four-leg Inverter

Normal state space is defined as,

$$\frac{d\mathbf{x}}{dt} = \mathbf{Ax} + \mathbf{Bu} + \mathbf{Ed}; \quad \mathbf{y} = \mathbf{Cx}. \tag{1}$$

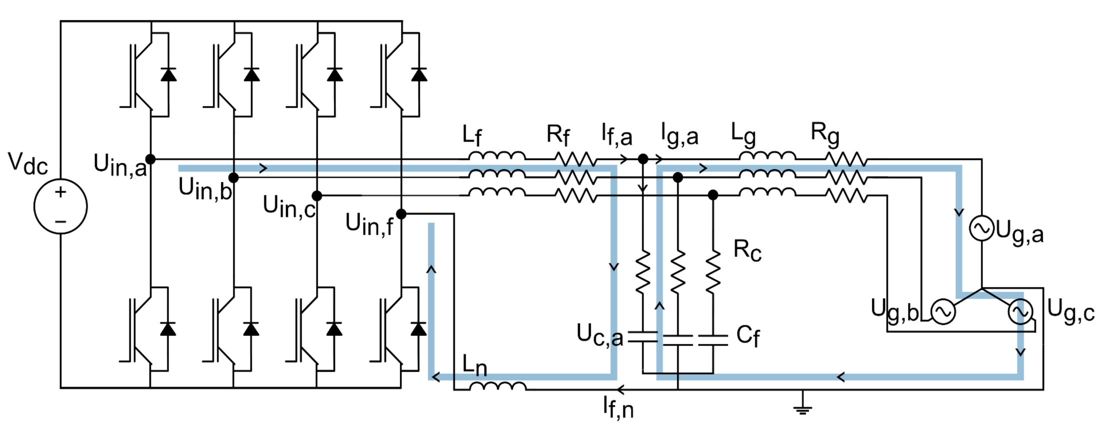

Fig. 1: Three-phase four-leg VSI with LCL filter

From Fig. 1, the following three state equations are formulated using Kirchoff's voltage and current law.

$$\frac{di_{f,abc}}{dt} = -\frac{R_f + R_c}{\mathbf{L}'} i_{f,abc} + \frac{R_c}{\mathbf{L}'} i_{g,abc} - \frac{1}{\mathbf{L}'} u_{c,abc} + \frac{1}{\mathbf{L}'} u_{in,abc-f}, \tag{2}$$

$$\frac{di_{g,abc}}{dt} = -\frac{R_c}{L_g} i_{f,abc} - \frac{R_g + R_c}{L_g} i_{g,abc} + \frac{1}{L_g} u_{c,abc} - \frac{1}{L_g} u_{g,abc}, \tag{3}$$

$$\frac{du_{c,abc}}{dt} = \frac{1}{C_f} i_{f,abc} - \frac{1}{C_f} i_{g,abc}. \tag{4}$$

Rearranging (2)-(4),

$$\frac{d\mathbf{x}}{dt} = \begin{bmatrix} -(R_f+R_c)L'^{-1} & R_cL'^{-1} & -L'^{-1} \\ -\frac{R_c}{L_g}I_3 & -\frac{(R_c+R_g)}{L_g}I_3 & \frac{1}{L_g}I_3 \\ -\frac{1}{C_f}I_3 & -\frac{1}{C_f}I_3 & 0_3 \end{bmatrix} \mathbf{x} + \begin{bmatrix} L'^{-1} \\ 0_{6\times 3} \end{bmatrix} \mathbf{u} + \begin{bmatrix} 0_3 \\ -(1/L_g)I_3 \\ 0_3 \end{bmatrix} \mathbf{d}, \tag{5}$$

$$\mathbf{y} = \begin{bmatrix} 0_3 & I_3 & 0_3 \end{bmatrix} \mathbf{x}. \tag{6}$$

State vector, control input, disturbance and output vector are respectively,

$$\mathbf{x} = \begin{bmatrix} i_{f,abc} & i_{g,abc} & u_{c,abc} \end{bmatrix}^\top; \quad \mathbf{u} = \begin{bmatrix} u_{in,abc} \end{bmatrix}^\top; \mathbf{d} = \begin{bmatrix} u_{g,abc} \end{bmatrix}^\top; \quad \mathbf{y} = \begin{bmatrix} i_{g,abc} \end{bmatrix}^\top.$$

and,

$$\mathbf{L}' = \begin{bmatrix} L_f + L_n & L_n & L_n \\ L_n & L_f + L_n & L_n \\ L_n & L_n & L_n + L_f \end{bmatrix}$$

Full State Observer Design

To reduce sensors full state observer is used.

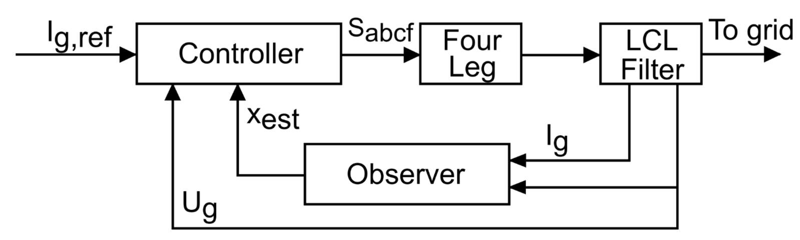

Fig. 2: Observer design for four-leg inverter

A full state Luenberger observer is defined in (7) where all three states are estimated using grid current and voltage as sensor feedback.

$$\frac{d\hat{\mathbf{x}}}{dt} = \mathbf{A\hat{x}} + \mathbf{Bu} + \mathbf{Ed} + \hat{\mathbf{u_{obs}}}, \tag{7}$$

$$\hat{\mathbf{y}} = \mathbf{C\hat{x}}, \tag{8}$$

$$\hat{\mathbf{u_{obs}}} = \mathbf{L}(\mathbf{y} - \hat{\mathbf{y}}) = \mathbf{LC}(\mathbf{x} - \hat{\mathbf{x}}). \tag{9}$$

Predictive Controller Design

Control input is absent in (3) which defines the grid current dynamics. Hence LCL filter is generally approximated [9] as L filter for the controller and is expressed in (10).

$$\frac{di_{g,abc}}{dt} = -\frac{R_f}{\mathbf{L}'} i_{g,abc} - \frac{1}{\mathbf{L}'} u_{g,abc} + \frac{1}{\mathbf{L}'} u_{in,abc-f} \tag{10}$$

state	S_a	S_b	S_c	S_f	state	S_a	S_b	S_c	S_f
1	1	1	1	1	9	0	1	1	1
2	1	1	1	0	10	0	1	1	0
3	1	1	0	1	11	0	1	0	1
4	1	1	0	0	12	0	1	0	0
5	1	0	1	1	13	0	0	1	1
6	1	0	1	0	14	0	0	1	0
7	1	0	0	1	15	0	0	0	1
8	1	0	0	0	16	0	0	0	0

Tab. 1: Four-leg inverter discrete switching states

Euler's forward difference formula,

$$\frac{dx}{dt} = \frac{x[k+1] - x[k]}{T_s} \tag{11}$$

Contd. in next column…

Control input discretization using Tab. 1,

$$u_{in,abc-f} = V_{DC} S_{abc-f} = V_{DC} \begin{bmatrix} S_a - S_f \\ S_b - S_f \\ S_c - S_f \end{bmatrix}. \tag{12}$$

Using (11) and (12), (10) rewritten as,

$$i_{f,abc}[k+1] = \left(\frac{\mathbf{L}' - R_f T_s \mathbf{I_3}}{\mathbf{L}'}\right) i_{f,abc}[k] - \frac{T_s}{\mathbf{L}'} u_{g,abc}[k] + \frac{T_s}{\mathbf{L}'} u_{in,abc-f}[k]. \tag{13}$$

Instantaneous active power at PCC,

$$P_{abc} = U_{g,a}.I_{g,a} + U_{g,b}.I_{g,b} + U_{g,c}.I_{g,c} \tag{15}$$

Filter current reference is,

$$i_{f,abc,ref} = K_i \int (P_{abc,desired} - P_{abc}) + K_p(P_{abc,desired} - P_{abc}). \tag{16}$$

Predictive cost function,

$$J(S)[k+1] = (i_{f,abc,ref}[k+1] - i_{f,abc,estimated}[k+1](S))^2 + \alpha_{sw} N(S)[k+1] \tag{14}$$

$$S_{k+1} = \texttt{argmin}(J(S)).$$

Note: α_{sw} is the weight attached to the toggle in states to limit excessive switching.

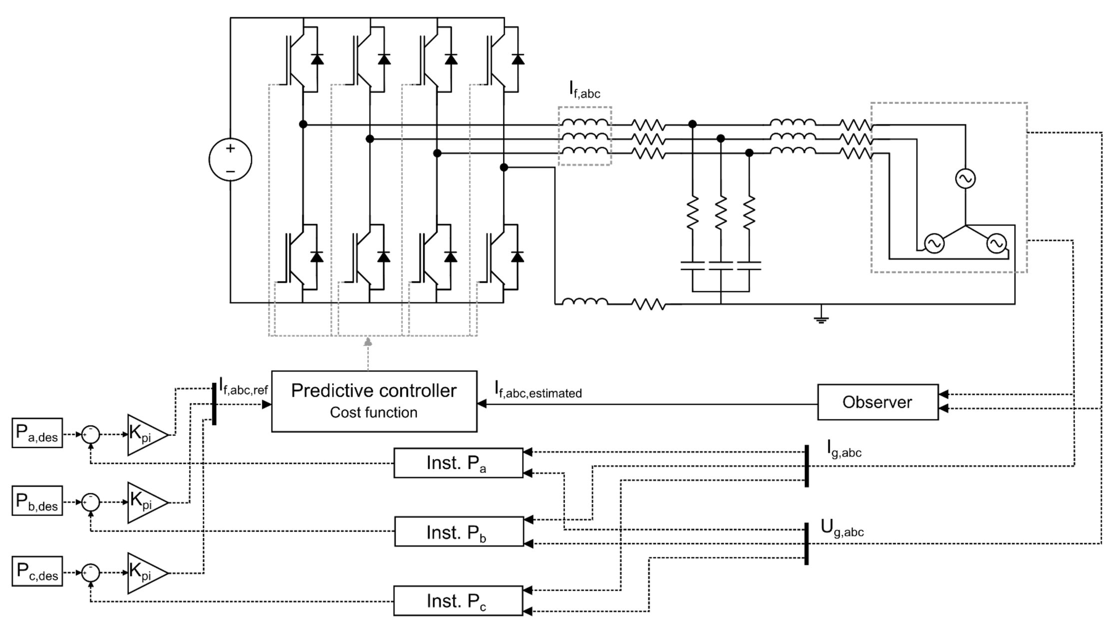

Fig. 3: Four-leg VSI, LCL filter, MPC with active power feedback

Results

V_g	400V 3ph rms, 50Hz	T_s	$50\mu s$
V_{DC}	800V(VSI)	F_{sw}	$< 5kHz$ per leg
L_f, L_n, L_g	3mH, 3mH, 1mH	Solver	Discrete, fixed-step
R_f, R_c, R_g	0.01Ω	K_p	$1e^{-3}$
C_f	$300\mu F$	K_i	$8e^{-1}$

Tab. 2: MATLAB/Simulink simulation settings

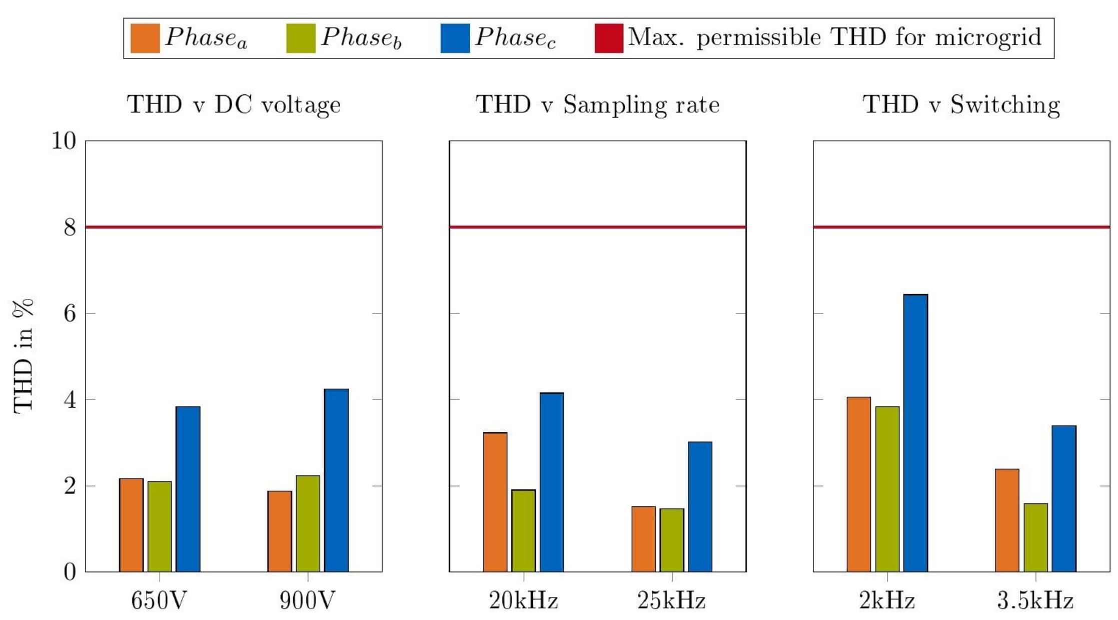

Fig. 4: Total Harmonic Distortion at different operating points

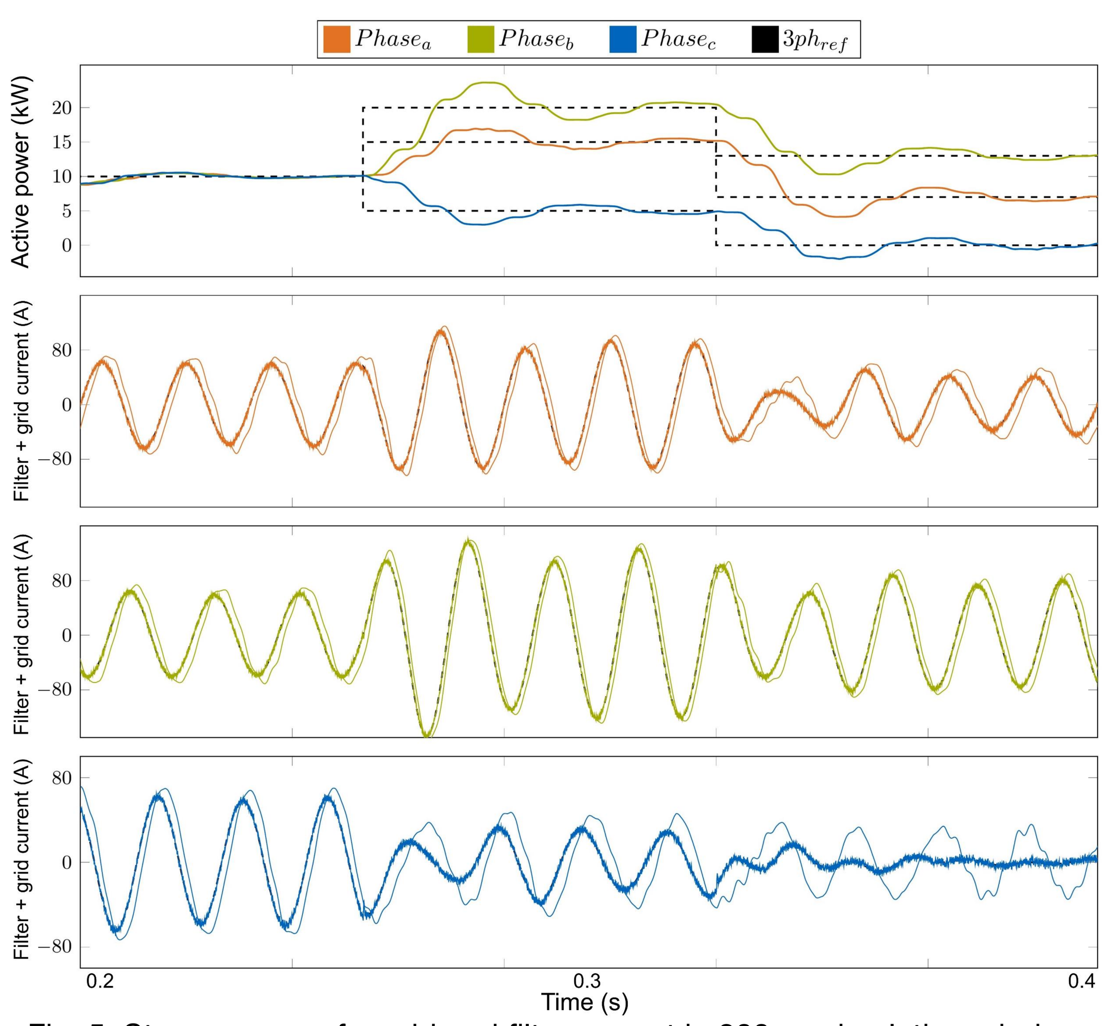

Fig. 5: Step response for grid and filter current in 200ms simulation window

- New aggregate controller – Four-leg + Predictive control + Active power feedback + a-b-c domain was proposed.
- Max. THD level set at 8% from IEEE 519-2014 with ratio of short circuit to full load current at PCC within 20 – 50.
- 2kHz switching at <6% THD with 20kHz sampling rate.
- Power step response converges in ~3 cycles.

Future Work

- Adaptive tuning of active power feedback loop.
- Phase error correction.
- Extension for Impedance source inverters (ZSI).
- Harmonic injection to suppress voltage distortion using similar controllers and L-filter.

References

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