

Control of Kalman Filter Based Z-source Inverter in Photovoltaic applications

Abhishek Gubbi Basavaraj¹, Woonki Na², Nan Wang³, Jonghoon Kim⁴ and Taehyung Kim⁵

1: <mailto:abhishekgubbib@gmail.com>, 2: wkna@csufresno.edu, 3: nwang@csufresno.edu, 4: whdgns0422@cnu.ac.kr,
5: taehyung@umich.edu

^{1,2,3}Department of Electrical and Computer Engineering, California State University, Fresno, CA, USA

⁴Department of Electrical Engineering, Chungnam National University, Daejeon, Korea

⁵Department of Electrical and Computer Engineering, University of Michigan-Dearborn, Dearborn, MI, USA

Abstract-- In this research, a Kalman filter-based Z-source inverter is proposed with an enhanced control algorithm for Maximum Power Point Tracking(MPPT) and this capacitor voltage stabilization. By implementing Unified Linear Kalman Filter Algorithm with Capacitor Voltage Control (CVC) algorithm for the Z-source inverter, the Kalman Filter can track Maximum Power Point (MPP) faster than traditional algorithm such as Perturb and Observation (P&O) algorithm, that has a minimum impact on rapidly changing atmospheric conditions. Thus, by using the Integrated Kalman Filter and CVC algorithm we can achieve faster, effective and capacitor voltage regulation at the same time. The effectiveness of this proposed Kalman Filter with CVC Algorithm for Z-source inverter is validated in MATLAB/Simulink and a hardware prototype has been built to verify the simulation and theoretical results.

Keywords— Kalman filter, Z-source Inverter, Control

I. INTRODUCTION

Lately, due to ever increasing demand for energy, people have explored many ways of energy sources like nuclear energy, fossil fuel energy, Hydropower and renewable energy resources. Fossil fuel has been the conventional energy sources for many years. However, there is a reduction in the fossil fuel resources in recent days, and due to increase in usage of fossil fuel the harmful gas emitted when it is burnt, i.e., gases like carbon dioxide and sulfur oxides have a detrimental effect to the environment. This effect and coupled with increasing energy demand has let to explore many renewable energy resources such as solar, biomass, wind energy, geothermal energy and hydroelectric power. According to recent studies, there have been increasing trends in the usage of renewable energy especially solar and wind energy has been rapidly growing in each passing year. There has been extensive research has been made to harvest renewable energy resources to convert into electrical energy. Every year new research has been done on increasing the efficiency of renewable energy conversions like designing converter strategies or new algorithms for maximum power tracking in wind and solar energy etc. In the quest to increase the efficiency of the solar power system, this research proposes Kalman Filter Based Z-source Inverters. Also, there have been increasing efforts to harvest renewable energy. Out of those, solar energy is a very popular solution as the solar energy is available everywhere and it can be converted into electrical energy without any

environmental pollution. However, conversion of solar energy requires continuous tracking. There has been increasing research on maximum power point tracking(MPPT) algorithms for the development of very efficient and low-cost solar energy systems. Also, there have been various studies on different power conversion systems(PCS) to reduce the switching loss which usually occurs in DC-AC or DC-DC power conversion. A Z-source inverter(ZSI) is a result of one of those studies, which reduces the switching losses that take place in two-stage power converters, and it offers a much better solution to both DC-DC and DC-AC in a single stage hence reducing the power loss[1]. A ZSI is highly suitable for an application like driving induction motors where there are huge voltage fluctuations and provides better performance due to its impedance matching network. There are many control algorithms proposed to control inverter or Z-source output voltage as well as AC Inverters output voltage.[2-5] In this study, a Kalman Filter based Z-source inverter design and control is described in section II. Section III describes the validation results obtained by the system and section V address the conclusion of the paper.

II. Z-SOURCE INVERTER

Impedance-source converter popularly called as Z-source converter utilizes an impedance circuit to couple the power source with the main circuit. The features provided by the Z-source inverter[1] is unique compared to the traditional voltage fed or current fed converters. It can be applied to all AC-DC, DC-AC and DC-DC applications. The three-phase Z-source inverter has nine switching vectors(states) unlike the traditional three-phase inverter, which has six active vectors when DC voltage is excited across the load and two zero vectors when load terminals are shorted through either by lower or upper switching devices. However, Z-source has one additional zero vector when the load terminals are shorted. This third zero vector is called as shoot-through zero vector. Because it would cause a shoot-through, this zero vector is forbidden in the traditional voltage-source inverter. The shoot-through vector can be generated by seven different ways: shoot through via any one phase leg, a combination of any two-phase legs and all three phase legs. The shoot-through zero state provides the unique buck-boost feature to the Z-source inverter.

A. Z-source Inverter Control

To design control system, a transfer function of the dynamic properties of the Z-source inverter is to be derived. The state space average model of the Z-source inverter is used to get the desired converter transfer function. We can simplify the Z-source coupled single-phase inverter as shown below in Fig.1. In Fig.1, S_2 and S_1 are replaced by the inverter and the input diode respectively. The shoot-through duty is cycle is defined by the S_2 duty cycle, D_o . In the Z-source network, there are two dynamic states[1]. During shoot-through state switch, S_1 will be open, and S_2 will be closed, that makes sure the input energy will not be transferred to the load. There will be the distribution of the energy transfer between inductors and capacitors in Z-network. The actual power transfer will happen during non-shoot-through states. The control strategy of the shown in Fig. 2 and 3. The control to voltage transfer function of the Z-network is given by

$$G_{Vcd}(s) = \frac{V_c}{D_o} \quad (1)$$

$$= \frac{VD(2V_c - V_{dc} - RI_{Load}) + (r+R)(I_{Load} - 2I_L) - sL(2I_L - I_{LLoad})}{s^2LC + sC(R+r) + (VD)^2} \quad (2)$$

The complete transfer function can be written by using the equations (1) and (2).

$$T(s) = G_c(s) \cdot H(s) \cdot \frac{V_c}{D_o} \cdot \frac{D_o}{V_m} = \frac{2}{V_{tri}} \cdot G_c(s) \cdot H(s) \cdot G_{Vcd}(s) \quad (3)$$

The plot of the $T(s)$, loop transfer function is plotted to show the unity gain and uncompensated loop. At unity gain, it has the crossover frequency of 230 Hz and phase margin of ten degrees. To improve the overall bandwidth and phase margin of the compensated loop, the PID compensator is designed which is shown below.

$$G_c(s) = G_{Co} \frac{(1 + \frac{s}{\omega_{z1}})(1 + \frac{s}{\omega_{z2}})}{s(1 + \frac{s}{\omega_p})} \quad (4)$$

The compensator gain G_{Co} is given by

$$G_{Co} = \frac{1}{|G_c(s) \cdot H(s) \cdot G(s) \cdot k_{shoot-through}|} \quad (5)$$

Fig. 4. shows the bode plots of the loop transfer function.

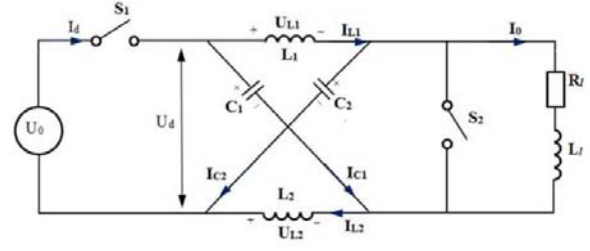


Fig. 1 Equivalent circuit of Z source network

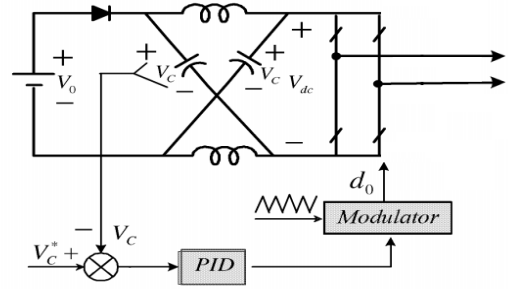


Fig. 2 Control strategy of Z source network

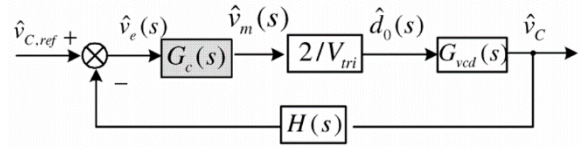


Fig.3. Block diagram of a voltage controller

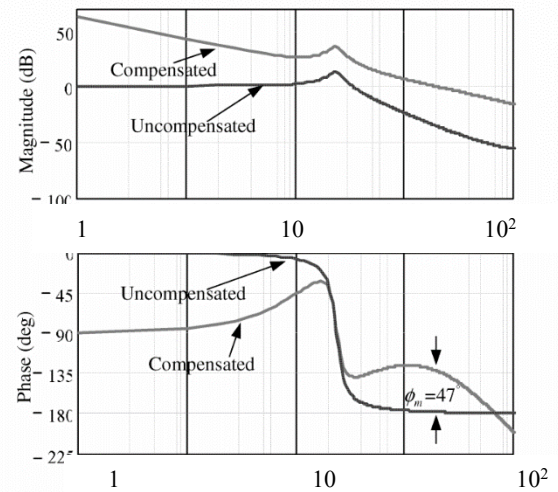


Fig. 4. Bode plots of loop transfer function

B. INTEGRATED CONTROL SYSTEM FOR Z-SOURCE BASED SINGLE PHASE INVERTER

In the previous section, we have designed the compensators for the standalone Z-source network which generates the shoot-through pulses and compensator for the single phase inverter which regulates the input side of the single-phase inverter. To regulate the input voltage of the PV panel with Z-source network and single phase inverter both controls are incorporated and it is shown in Fig.5.

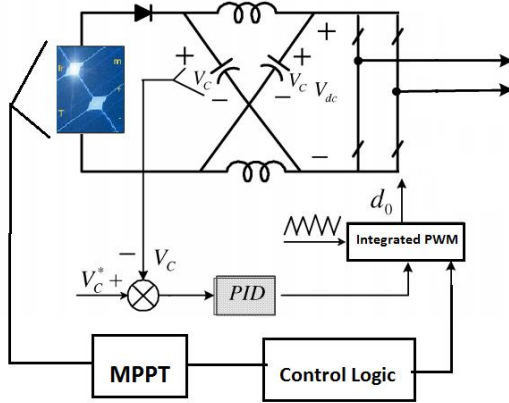


Fig. 5 Complete Control block for Z source network

Both the pulses, i.e., the shoot-through pulses generated for the Z-source network and pulses for the PV voltage control is mixed through integrated pulse generator which is shown in Fig. 6. Both the shoot-through(ST) and conventional pulses are sent through OR gate to generate the required pulses for the operation.

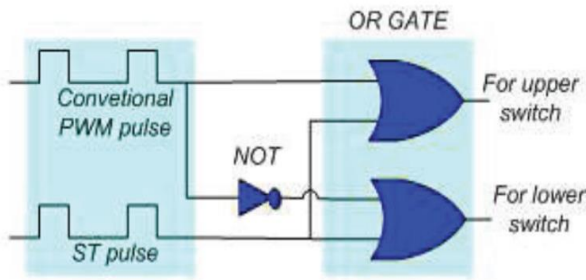


Fig. 6 Mixing gate signals

C. Kalman Filter

Kalman Filter is a state estimator or observer. However, the uniqueness of Kalman Filter is its estimation in noisy conditions or estimating noisy inputs. It uses the probability of noise covariance and estimates the state based on its linear behaviour of the state. Fig. 8 shows the general block diagram of the Kalman Filter.

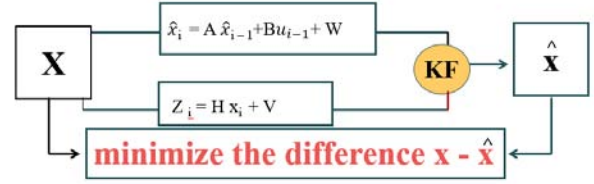


Fig. 6. Block diagram of a Kalman Filter

If $\hat{x}_t$ is the state at iteration t and z_t is the measured signal at t , following are the Kalman filter equations[12],

(i) Time Update – (Prediction state)

$$\hat{x}_{t-} = A \hat{x}_{t-1} + B u_{t-1} \quad (6)$$

$$z_{t-} = A z_t A^T + Q \quad (7)$$

Here process noise covariance is Q , $\hat{x}_{t-}$ be the state estimate at iteration t given by the results from previous iterations, $\hat{x}_t$ be the state estimate at iteration t given by the output measurement $\hat{y}_{t-}$, $\hat{z}_{t-}$ be the priori error covariance and z_t or z_{t-} be the posteriori error covariance. A & B are constants.

(ii) Measurement Update – (Correction State)

$$K_t = C^T Z_{t-} (C Z_{t-} C^T + R)^{-1} \quad (8)$$

$$\hat{x}_t = \hat{x}_{t-} + K_t (y_t - C \hat{x}_{t-}) \quad (9)$$

$$z_t = z_t (1 - K_t C) \quad (10)$$

R is the measurement noise covariance, K_t is the Kalman gain and C is constant. The above equations represent Linear Kalman filter implementation for a linear discrete system. The time update predicts next state estimate and error covariance. The estimates are then fed back to measurement update which acts as a corrector and corrects the estimated values. As the above cycle takes place in multiple iterations in turns, the noises are reduced and the error covariance z_t becomes closer to zero.

D. The proposed Kalman Filter based MPPT

The Power versus Voltage characteristics of PV array is a convex function where the peak point is called maximum power point. This can be expressed using the following equation,

$$V[n+1] = V[n] + M \frac{\Delta P[n]}{\Delta V[n]} \quad (11)$$

Here, M is the step size and $\frac{\Delta P[n]}{\Delta V[n]}$ is the instantaneous power slope of the PV module. By using the Kalman gain both the error covariance and the estimated voltage are corrected to $\hat{V}_{act}[n]$ and $H[n]$ in measurement update state. However, the feedback voltage $\hat{V}_{act}[n+1]$ and error covariance $H[n+1]$ is estimated by the time update equations.

(i) Time Update – (Prediction state)

$$\hat{V}[n+1]^- = \hat{V}[n] + M \frac{\Delta P[n]}{\Delta V[n]} \quad (12)$$

$$H[n+1]^- = H[n] + Q \quad (13)$$

(ii) Measurement Update – (Correction State)

$$K[n] = H[n]^{-1} (H[n]^{-1} + R)^{-1} \quad (14)$$

$$\hat{V}_{act}[n] = \hat{V}_{act}[n]^{-} + K[n] (V_{ref}[n] - \hat{V}_{act}[n]^{-}) \quad (15)$$

$$H[n] = (1 - K[n]) H[n]^{-} \quad (16)$$

The below figure shows the flow chart of proposed KF based MPPT. After the measurement of PV voltage and current at each nth state, the system computes the power and the difference in voltage and power. Using these measurements, the system executes time and measurement update stage. The estimated voltage is used to calculate duty cycle of the single phase inverter. These equations and measurements iterates continuously in a cycle.

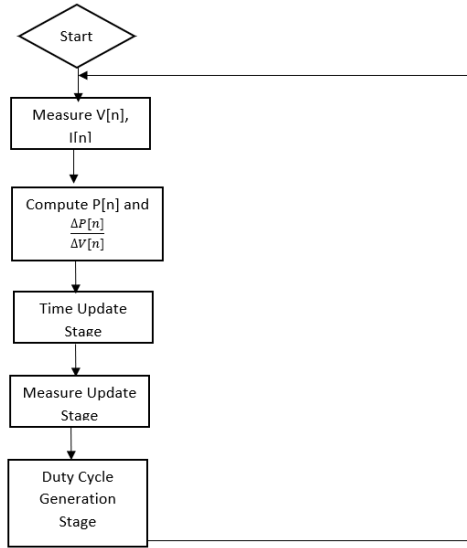


Fig. 7 KF based MPPT

III. RESULTS

Theoretical advantages of the Kalman Filter based Z-source inverter is verified by implementing in the MATLAB / SIMULINK. The simulation results present the analysis and performances of Kalman based Z-source and P&O based Z-source Inverter. The configuration of PV panel used for the simulation is shown in the below table.

Table 1: Electrical Specifications of Test PV panel

Parameters	Values
Max. Power Voltage	17.9 V
Max. Power Current	0.51 A
Open Circuit Voltage	22.5 V
Short Circuit Current	0.61 A

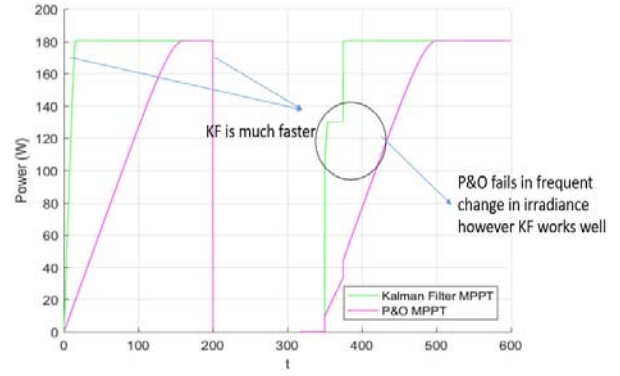


Fig. 8 KF vs P&O simulation

Fig. 8 shows how the Kalman filter is faster compared to the P&O algorithm. We can see that Kalman took 5ms to track the maximum power. However, P&O took around 200ms to track. Fig. 8 also shows even during the sudden changes in the irradiance Kalman filter has been highly efficient in tracking, whereas P&O algorithm failed to see sudden changes.

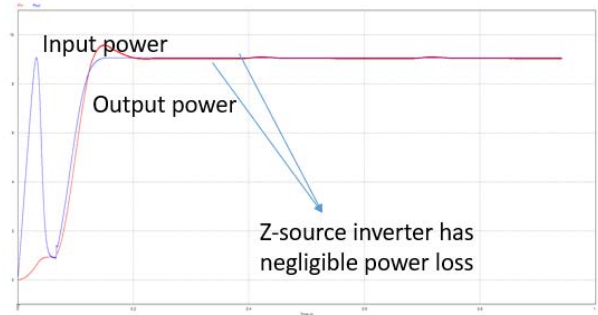


Fig. 9 Power loss comparison

Fig. 9 shows the power loss comparison between the power regulator and Z-source inverter. The experimental setup for the proposed system for a photovoltaic system is shown in Fig. 10.

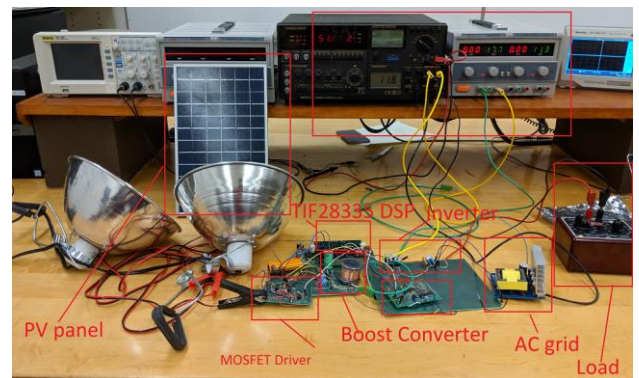


Fig.10 Experimental setup

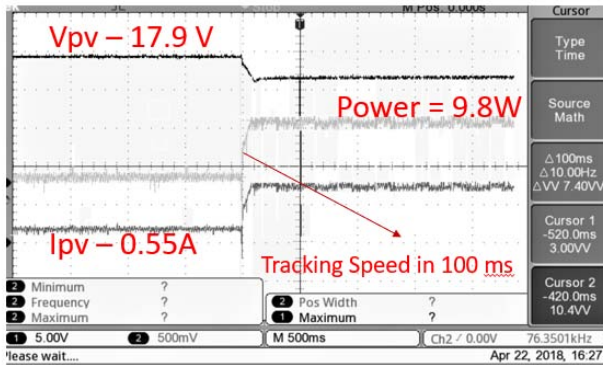


Fig. 11 PV Voltage, Current and Power for P&O MPPT Implementation

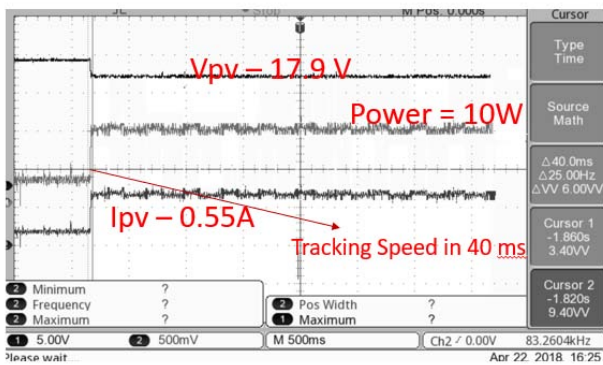


Fig. 12 PV Voltage, Current and Power for Kalman Filter MPPT Implementation

The performance of P & O algorithm is shown in the Fig. 11 and the performance of the proposed MPPT system with Kalman filter is shown in Fig. 11. The PV panel is of 10W, and is initialized to the open circuit voltage of 22.5 V. When the P and O algorithm is implemented using DSP TMS28335 the tracking time is of 100ms, however when Kalman filter is implemented the tracking time is as small as 40ms.

V. CONCLUSION

In this research, an improved hardware topology with Z-source inverter and highly efficient Kalman Filter Algorithm is proposed. The proposed control design is implemented for the grid-tied mode topology. The proposed model and its mechanism have been verified by simulation and experimental results.

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