The Pennsylvania State University

The Graduate School

**DESIGN AND IMPLEMENTATION OF KALMAN FILTER-BASED**

**MPC-MPPT ALGORITHM FOR PV DC-DC CONVERTER SYSTEMS**

A Thesis in

Electrical Engineering

By

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**ABSTRACT**

DC-DC converters and their respective control systems are commonly used in photovoltaic (PV) energy systems in order to maximize the power that can be extracted from a PV source and supply a steady DC signal to a load while providing a desired amount of gain. Since PV cells have low power efficiency and contain variable I-V and P-V characteristics, a maximum power point tracking-based (MPPT) control system for the converter must be designed and implemented in order for the converter to consistently draw maximum possible power from the PV source and thus apply maximum possible power to a load. In this thesis, a Kalman Filter is combined with the Incremental Conductance algorithm in order to track maximum PV power and control a custom topology DC-DC boost converter in an optimal control scheme comparable to that of Model Predictive Control. The Kalman Filter functions to estimate system states, filter noise from existing sensors, and predict future states of the system given a change in duty cycle, thus allowing for a reduction in sensor count and an increase in algorithm accuracy and efficiency. The Incremental Conductance algorithm generates a desired reference signal that is compared to the predicted signals generated from the Kalman Filter and control of the converter’s duty cycle is applied as needed. Given that an averaged state space model can be derived for the controlled DC-DC converter, this design can be implemented across any non-isolated circuit topology, and functions to improve upon existing designs by reducing sensor count, filtering noise, and providing the processor system with access to complete state information of the circuit it is controlling. This paper explains the design, implementation, experimentation, and results of the proposed system across various circuit topologies both in software simulation and hardware experimentation.

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**Chapter 1**

**Introduction**

**1.1 Overview**

Driven by both increases in population growth and energy-consuming technologies, the energy requirements of both developed and developing countries is consistently increasing every year [1][2]. However, conventional energy resources such as fossil fuels are reducing in availability and come with the cost of having a harmful impact on the environment [3]. The world is therefore undergoing a transitional period where its focus on energy extraction is switching from fossil fuels to renewables. Of the types of renewable energy resources available, solar energy extraction through the use of photovoltaic (PV) cells, modules, and arrays have gained a large amount of attention. This is primarily due to solar energy being readily available and capable of being extracted anywhere with sunlight, as well as because PV systems have minimal operational and maintenance costs. Additionally, the overall cost of development and implementation of PV systems is continuing to decrease [4][5][6].

However, PV power efficiency is considerably low, and the maximum power point that exists within a PV system at any given time is dependent on many variables, which include environmental temperature, solar irradiance, shadowing effects, PV surface cleanliness, PV cell and array arrangement, as well as other internal characteristics of the PV cell itself [7]. This causes complexity in determining the optimal design of a DC-DC converter that must function as a link between a PV array and a load. Due to constant changes in the previously stated variables, the maximum power point is constantly changing with time, and continuous adjustments to the circuit that functions to extract power must be made. Therefore, designing a maximum power-point tracking (MPPT) controlled converter system that both provides a steady output voltage while also tracking and maintaining maximum power efficiency is of high importance, and is considered to be major focus of solar energy research [8].

**1.2 Motivation**

A large amount of research has been conducted for the development and testing of various MPPT algorithms [9]. These models have been designed and implemented in order to transfer energy at its optimum efficiency through the use of controllers with high tracking accuracy, as well as provide fast and stable transient and steady-state responses, capable of driving a steady output voltage containing minimum oscillations. The overall effectiveness of these designs can be determined through analysis of power efficiency, cost, hardware complexity, number of sensors, steady state tracking efficiency, algorithm complexity, transient response, and steady state oscillation [9] [10]. Through this analysis, it can be seen that many of these proposed systems have excessive levels of complexity and cost, do not perform efficiently, or come with significant design tradeoffs [10][11]. As a typical example, a simple circuit design topology could have few components and simple algorithms, but will typically track MPP poorly and have low power efficiency. In contrast, a complex design topology and algorithm could track MPP efficiently and have high boost efficiency, but also contain many system components and complex algorithms. Existing research in this area also offers little in terms of hardware implementation and experimentation, and often comes to conclusions based on software simulation alone. Because of this, ideal system conditions are typically simulated, and real-world disturbances such as noise from sensors and the circuit are ignored and problem criteria such as how noise and other disturbances could affect the control algorithm and PV system as a whole are typically not considered.

The objective of this project is to model a Kalman filter-based MPC-MPPT algorithm in order to control the duty cycle on a DC-DC converter, which thus controls its output load voltage-to-current ratio. The Kalman filter will estimates states of the system in order to reduce sensor count and filter any system and output noise that would be present in real applications. It also functions to predict future states of the system given an incremental decrease or increase in duty cycle. It then passes this information to an Incremental Conductance algorithm which finds the maximum power point from the provided state information and creates a reference photovoltaic current signal that will be compared to the predicted states from the Kalman filter and, through choosing the predicted state that most closely resembles the reference signal, a change in duty cycle will occur. This process of state prediction and reference comparison is structurally similar to a Model Predictive Control System. This design attempts to offset the multiple sensors needed for Incremental Conductance and MPC-Increment Conductance algorithms, and further optimize the efficiency of the system through noise removal and accurate future state prediction.

The Kalman filter utilizes an averaged state space model of the DC-DC converter being controlled and, given that an averaged state space model can be derived, this methodology can be used for any non-isolated circuit topology. The algorithm is developed and implemented in MATLAB and Simulink, and is further developed on FPGA hardware for further testing.

**1.3 Thesis Structure**

This thesis functions to review existing literature surrounding PV DC-DC converter systems and MPPT algorithms, perform mathematical modeling of the proposed systems, implement the models in simulation software and hardware, and analyze and discuss acquired results. Chapter 2 discusses the existing literature regarding photovoltaics, converter topologies, MPPT Algorithms, Model Predictive Control, and Kalman Filters. Chapter 3 discusses the methodologies used to derive the mathematical models of the proposed system to be designed and tested. Chapter 4 discusses the experimentation process. Chapter 5 discusses the results obtained from the experiment. Chapter 6 discusses concluding remarks and future work.

**Chapter 2**

**Background**

**2.1 Overview**

Existing research explores the various circuit topologies, MPPT algorithms, control algorithms, and other design criteria for designing the best possible PV DC-DC converter given specific constraints. There is no single system design that is considered best since certain design specifications could be considered more favorable in a specific application when compared to others. For example, a certain PV system design that is considered optimal for satellite applications could also be considered suboptimal for residential applications [12]. Likewise, a PV system designed to regulate charge to a low-voltage battery pack will benefit from very specific design criteria while a PV system designed to be directly fed into a high-voltage utility grid will not benefit from the same criteria [13].

Since the goal of this project is to optimize for the high complexity that comes with high efficiency PV DC-DC converter topologies and algorithms, the analysis of literature focuses on research utilizing high complexity circuit topologies, high complexity MPPT and control algorithms, and/or high resource cost system designs. A review of boost efficiency, power efficiency, MPPT tracking efficiency, and controller efficiency is conducted to review overall system efficiency, and analysis of circuit resource utilization, algorithm complexity, and sensor count is performed in order to gauge overall system complexity. Additionally, fundamental yet necessary concepts such the functionality of photovoltaics and Kalman filters is discussed.

**2.2 Photovoltaics**

Photovoltaic energy systems convert solar irradiation to electricity through the use of two-layer PN junctions. Photons that reach the junction increase charge carriers and thus create a voltage difference which results in current flow through a respective circuit [14]. The equivalent circuit of a solar cell can be represented using the following equation:

(X)

Where is solar-generated current, is diode saturation current, thermal array voltage, is number of cells in series, is diode ideality constant, is series resistance, and is parallel resistance [15].

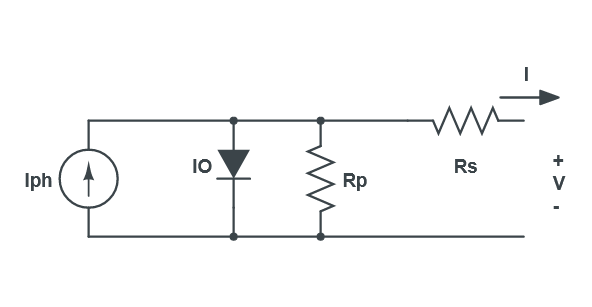


Figure X. Equivalent circuit model of a solar cell

The value of is dependent on both solar irradiance and temperature, as seen in the following:

(X)

Where is solar current generated at nominal conditions, is irradiance, is nominal irradiance, is cell temperature, is nominal cell temperature, and is short-circuit current/temperature coefficient [15]. Furthermore, the value of the diode saturation current, is dependent on temperature as well, with the following:

(X)

Where is nominal diode saturation current, is electron charge, is Boltzmann’s constant, and is bandgap energy [15]. can further be expressed as follows:

(X)

Where is open circuit voltage, is nominal cell thermal voltage, and is short circuit nominal current.

From the previous equations, the relationship of the solar cell’s output current and voltage can be analyzed graphically through its I-V relationship curve.



Figure X. I-V and P-V characteristics of Kyocera Solar KC200GT solar cell with a fixed temperature of 25 deg. C and specified irradiances of 600, 800, 1000, and 1200 with the cell’s maximum power point dotted

From figure X, it can be seen that irradiance changes cause changes in the characteristics of the PV cell’s I-V and P-V relationship when other factors are held constant.



Figure X. I-V and P-V characteristics of Kyocera Solar KC200GT solar cell with a fixed irradiance of 1000 and specified temperatures of 25, 50, 75, and 100 deg. C, with the cell’s maximum power point dotted

Furthermore, from figure X it can be seen that temperature changes cause changes in the solar cell’s I-V and P-V characteristics when other factors are held constant.

For any set of operational conditions, there is a specific voltage value and current value that results in maximum power output, known as the maximum power point [16]. This maximum power value can be obtained through the process of impedance matching a load that will allow for the desired voltage and current values to exist. From the previous figures, it can be concluded the maximum power point is constantly changing given constantly changing temperature and irradiance values, and therefore the point must be regularly tracked and the resulting load’s impedance must be regularly controlled.

**2.3 DC-DC Converter Topologies**

The load applied to the PV cell is typically of the form of a DC-DC converter system. Non-isolated boost converters are typically used in order to boost low PV voltages to a higher value so that an inverter can successfully apply the signal to the AC grid [17]. Likewise, buck converter topologies can be utilized for battery charging and universal power supply applications [18]. Non-isolated converters have the advantage of reducing system cost and improving system efficiency when compared to their isolated counterparts [19].

Research generally used in the design of PV DC-DC converter systems involve the use of custom topology boost, buck, buck-boost, SEPIC, cuk, flyback, dual-active bridge, and push-pull converters [13][20], as well as many other topologies that capitalize on achieving high gain, reduce switch voltage stress, or reduce the need for high duty cycles [19]. The overall classification for PV converter topologies can be ordered into isolated and non-isolated systems, where isolated systems are multi-staged in order to have complete separation of inputs and outputs, typically through the use of a transformer. High voltage applications typically benefit most from isolated systems [20]. In general, the non-isolated topology of the boost converter is considered most favorable for general applications, due to its low number of components, simple drive circuit, and non-pulsating input current (the input pulsates in correlation to the switching rate) [21]. At the same time, the main drawback of the boost converter is its limited gain capabilities, as well as the need for high voltage rating diodes, and the presence of copper and core losses in the inductor. Many custom designed boost converter topologies attempt to perform voltage multiplying in order to address problems with gain. However, this typically comes with the cost of increased components, increased voltage stress, and variable efficiency ratios given the condition of the system (i.e., input voltage, switching frequency) [21].

The topologies explored in this paper involve a custom, high gain boost converter designed by the authors of [11], the bidirectional SEPIC converter presented by the authors of [22], as well as the synchronous buck converter presented by the authors of [18].

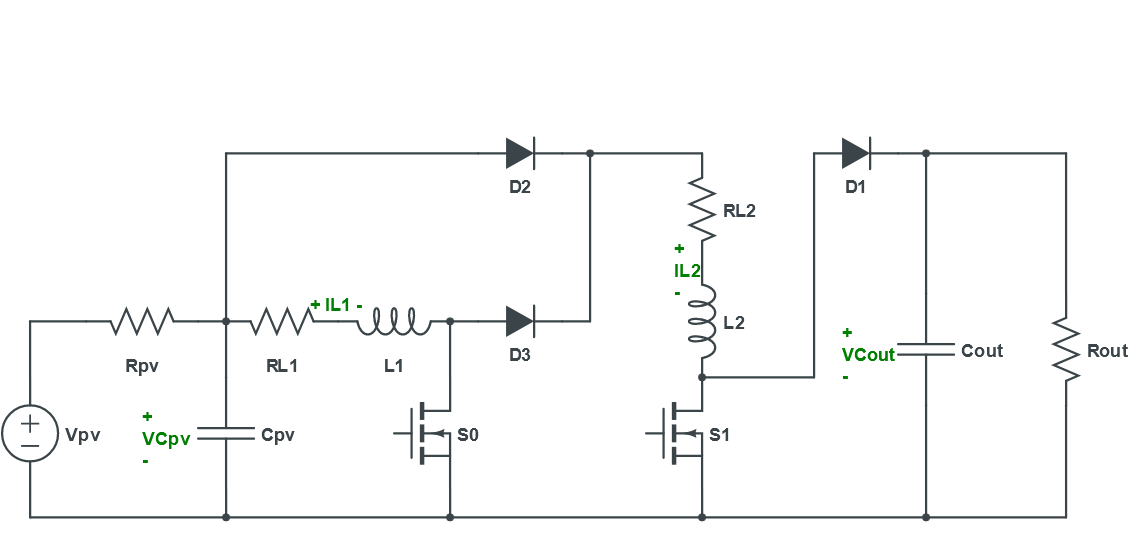


Figure X: Custom Topology High Gain Boost Converter

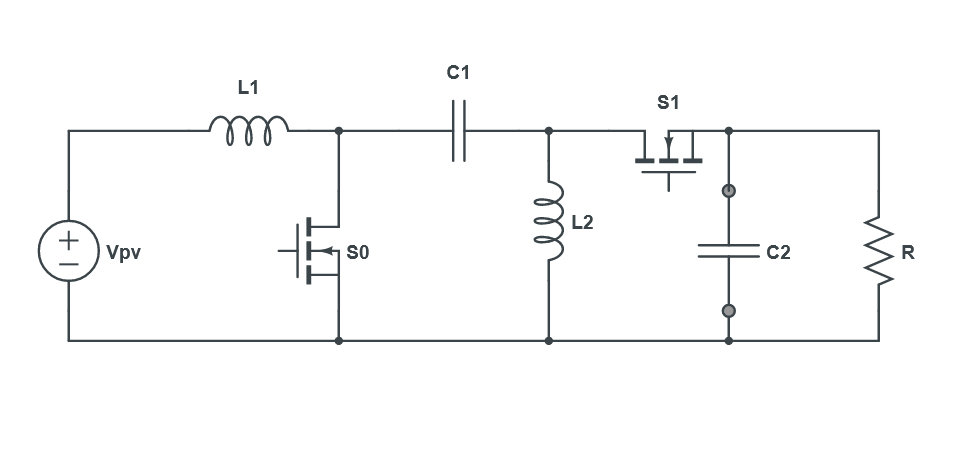


Figure X: Bidirectional SEPIC Converter

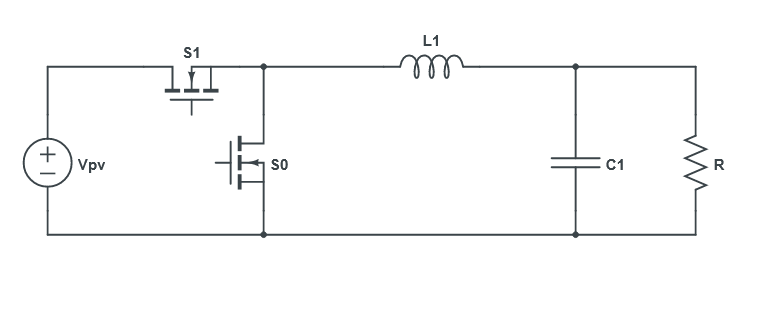


Figure X: Synchronous Buck Converter

Boost converters typically have higher efficiency compared to SEPIC converters [21]. However, SEPIC converters are typically favored over traditional buck-boost converters for higher efficiency rates and continuous input current [21]. Boost converters suffer from the need of high switching conduction rates, causing sharp current spikes and high current stress, a problem the authors of [11] attempt to address through the custom designed topology [11][21]. The synchronous buck converter functions to reduce diode conduction losses seen in the traditional buck converter topology [18].

**2.4 MPPT Algorithms and Controllers**

Some of the most commonly used MPPT algorithms throughout literature involve the Incremental Conductance, Perturb and Observe, Fuzzy Logic Controller, Neural Network, and or feedback control algorithms [12]. MPPT algorithms can be categorized into three classes: Direct, Indirect, and Soft Computing. Direct MPPT applies control signals to the converter and observes how those signals affect the MPP through observation. Indirect MPPT exploits characteristics of the PV panel in order to determine MPP. Soft computing MPPT uses computing methods that are applied to approximated and predictive models [23]. The most popular forms of MPPT fall within the Direct class and most commonly involve variations on the Perturb and Observer algorithm, as well the Incremental Conductance algorithm [23]. The P&O algorithm is considered a simple algorithm but has drawbacks due to the system never achieving steady state, errors occurring when irradiance drops below 400 as well as rapid changes in atmospheric conditions causing tracking failures [24]. P&O functions by applying a perturbation of to the duty cycle of the converter with a perturbation frequency of . It is then observed if the resultant change in PV power is positive or negative. If positive, the perturbation continues in the same direction. If negative, the perturbation is applied in the opposite direction [25].

The Incremental Conductance algorithm has a higher level of algorithmic complexity which results in the need for high sampling rates, digital implementation, and high levels of speed control. However, it is capable of reducing output oscillations by reaching a steady state. It can also track faster than P&O, and has a very high degree of accuracy [12][24]. Incremental Conductance functions by assuming that the rate of change of PV power with respect to voltage is equal to zero at maximum power point, as follows [26]:

(X)

Which can be rearranged as follows:

(X)

From these equations, the following inequalities can be derived to determine where the system is with respect to the maximum power point [26]:

(X)

In other words, the algorithm identifies where on the photovoltaic P-V curve it is located by calculating the relation between the rate of change of conductance instantaneous conductance.

The MPPT algorithms function to track maximum power points, and therefore either aid in the control of what is typically the voltage or current parameters of the circuit, or directly control the system on its own. The MPPT algorithms that only identify what voltage or current values are needed for MPP require a controller to implement control (Current/Voltage MPPT Control). This occurs through the design of a control system that can interpret the desired reference MPPT signal, compare it to the existing MPPT signal, apply control as needed. This contrasts to MPPT algorithms that directly control the duty cycle of the circuit switches (Direct Duty Cycle MPPT Control), where the control system is built into the algorithm and an additional controller is not needed [23].

**2.5 Model Predictive Control**

With the advent of high-speed microprocessor technology, applications of model predictive control in power electronics have become increasingly popular [27]. The main principal of model predictive control involves predicting future behavior of desired control variables over a predetermined time horizon [28]. The MPC system typically does this by having information about the system it is controlling, typically through the use of a discrete state space model, as seen below:

(X)

A cost function is then compared with the predicted values at the end of the time horizon, as seen below:

(X)

Where N is time horizon. The predicted value that minimizes the cost function at time N is chosen, and the control actuation associated with the value is applied only for time k+1. The sample time then moves up one step and the entire process is repeated over again [28].

With DC-DC converters, the MPC algorithm functions to predict future switching states of the system through the mathematical model of the converter, define a cost function that represents the desired behavior of the system (typically correlated to maximum power point), and applying control to the switching state associated to the input that minimizes the cost function. This is considered useful when PV systems undergo rapid atmospheric condition changes. The cost function is typically represented as a PV current or PV voltage reference signal generated from the P&O or Incremental Conductance MPPT algorithms [29].

MPC techniques typically provide fast dynamic responses with high stability when compared to classic control techniques [30]. Furthermore, robust control, higher convergence speeds, and less steady state ripple is seen in simulation of MPC-MPPT systems [31][32][33]. However, hardware implementation has shown for these results to be inconclusive [29].

**2.6 Kalman Filters**

The Kalman filter is an algorithm that uses a series of data observed over time to estimate unknown system states with as much accuracy as possible. The Kalman filter further assumes that the data being observed contains both noise and disturbances [34]. The states estimated are based on linear dynamical systems presented in a state space format. The process model then defines how a state develops per unit timestep as follows:

(X)

Where is the state transition matrix, which is applied to the previous state vector , is the control-input matrix, which is applied to the previous control vector , and is the process noise vector, assumed to be a zero-mean Gaussian distributed white noise with a covariance matrix defined as [35]. The states of the process model are correlated to the measurement (or observation) of the system through the following equation:

(X)

Where is the measurement vector, is the measurement matrix, and is the measurement noise vector, assumed to be a zero-mean Gaussian distributed white noise with a covariance matrix defined as [35]. The goal of the Kalman filter is to estimate the state vector through consistent analysis and comparison to the measured output, , provided that the other system information (is provided.

The information from the previously mentioned models are then used in the following two-stage mathematical algorithm to form the structure of the Kalman Filter, where is the value of at time , given observations up to and including at time :

Predict:

(X)

Update:

(X)

Where equation XA is the predicted state estimate, equation XB is the predicted error covariance, equation XC is the measurement residual, equation XD is the Innovation covariance, equation XE is the Optimal Kalman gain, equation XF is the updated state estimate, and equation XG is the updated error covariance.

The prediction stage uses the existing input value to estimate the states of the system and the error covariance using previously estimated state estimates and error covariances. The update stage uses the existing output to determine the error in the prediction, create a gain that minimizes the error covariance, and applies said gain in order to correct or ‘update’ the existing state and error estimations.

This two-step algorithm is executed in its entirety for each discrete timestep k, with previously estimated values being recursively fed back into the algorithm at the next time step. This can be seen as a form of feedback control, in that the filter estimates the process state at time k, and then obtains feedback in the form of noisy measurements. It can also further be considered a form of optimal control, in that it minimizes the estimated error covariance [36].

**2.6 Similar Designs**

Research that closely resembles the design and implementation goals of this project involve the use of high gain boost converter topologies, Incremental Conductance or Perturb and Observe MPPT systems, and some form of controller and/or observer designs for driving the circuit to its desired voltage and current values. The authors from [11] used the same circuit topology (2 capacitor, 2 inductor) and the same MPPT algorithm (IncCond) and controller (MPC), but did not integrate any state estimator, resulting in a system that required multiple sensors. They concluded that there were power efficiency problems at certain input voltage levels. The authors from [37] used a 2 capacitor, 1 inductor boost topology that utilized an MPC P&O algorithm. The MPC model improved slow transient behavior and ripple of the P&O algorithm, and an Extended Kalman Filter (EKF) was added to the system to reduce sensors. However, only MATLAB simulations were used, which simplified the experiment to ideal conditions only. The authors from [38] used a buck-boost topology with an incremental conductance algorithm. They were able to conclude that the incremental conductance algorithm outperforms the P&O algorithm, but the boosting ratios on the buck-boost converter were considered low.

In exploring more broadly similar literature, the authors from [39] used a cuk converter with an ANN algorithm, but concluded that the cuk converter’s increased complexity does not outweigh its ability to perform better than the boost converter at lower irradiance levels. The authors only performed software simulation under ideal conditions. The authors from [40] used reinforcement learning on a 2 capacitor, 1 inductor boost converter, and concluded that there were small ripples present in the output, and MPPT control accuracy was weakened when an additional neural network was not used to approximate the states of the system.

**Chapter 3**

**Methodology**

**3.1 Circuit Model**

The first step in the system design involves creating a mathematical state space model of the circuit being controlled. The following shows the derivation of the bilinear switching and small signal averaged state space model for the high gain boost converter of [11] when resistors are added in series with the inductors. These two models are then modified to create a linearized state space model that depends on the duty cycle and the PV voltage that is more accurate than the averaged small signal model while still being linearized.

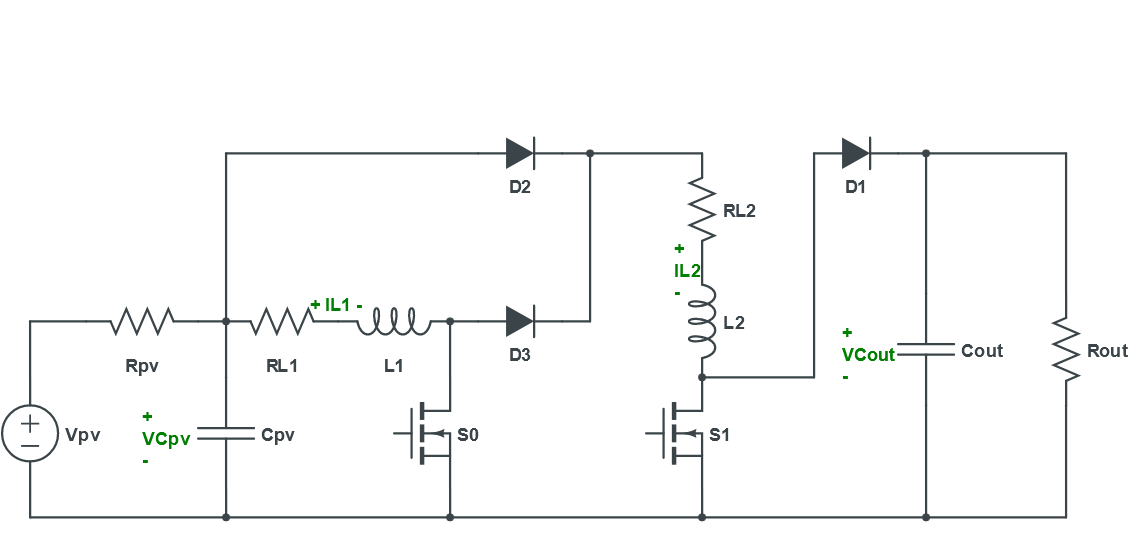


Figure X: Overall Circuit

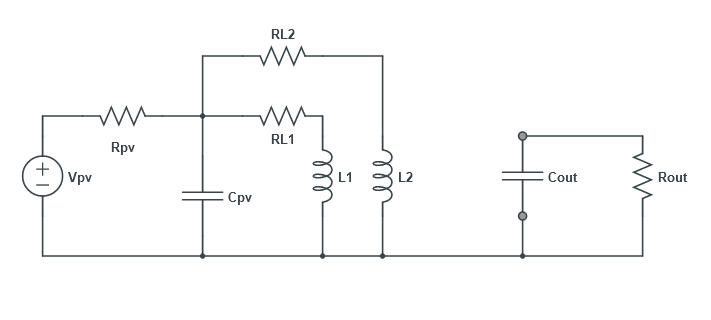


Figure X: circuit when switch is on

The KVL and KCL equations of the circuit when the switch is on are as follows:

(X)

The equations can be rearranged in terms of state variables as follows:

(X)

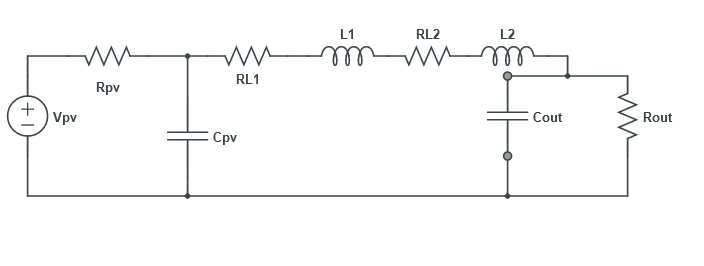


Figure X: circuit when switch is off

The KVL and KCL equations of the circuit when the switch is on are as follows:

(X)

The equations can be rearranged in terms of state variables as follows:

(X)

The two sets of equations can be combined into a single set of equations, incorporating both when the switch is on by distributing the variable U (representing the switch on) through the first set of equations, and when the switch is off by distributing (1-U) through the second set of equations. The following shows the results after combining equations, distributing values, and cancelling terms:

(X)

The bilinear switching model follows the format of , and the previous set of equations can be incorporated into the model as follows:

(X)

However, this model is not linear, nor is it in the typical state space form needed for the Kalman Filter. Therefore, the small signal averaged model, which is in the form of is developed by combining the A and B matrices of the switching model in terms of the averaged switching value, denoted as The B matrix is determined by determining the rate of change of the switch U after setting the rate of change of the state variables equal to zero and solving for the value of the unknown state variables.

(X)

However, the small signal averaged model proves to have issues with accuracy, and therefore the model is modified so that of the A matrix is replaced with the switching duty cycle D, and the B matrix is modified so that it incorporates the d matrix of the bilinear switching model, with the input, U replaced by . This is modified to the following state space model:

(X)

Given that the exact value of the duty cycle can be determined and access to the value of is possible, this model proves to have high accuracy in terms of representing the states of the circuit under consideration.

**3.2 Kalman Filter Design**

The Kalam filter used in this system assumes availability of , , and the existing duty cycle rate, at the existing time of sampling . That said, the need for access to can be removed by estimating its value using the gain equation associated with the corresponding DC-DC converter.

The Filter also requires a discretized state space model of the system it is observing. The previously stated state space model from equation X is discretized using the forward Euler method of approximation:

(X)

Where I is the identity matrix, and is the chosen sampling rate of the system. C and D matrices remain unchanged. The A and B matrices of the discretized state space model is then used as the F and B matrices of the Kalman filter algorithm seen in equation X, respectively. A C matrix is chosen as

(X)

Since is considered the output of the system. Q and R matrix coefficient values are chosen to scale with the amount of noise added to the simulation states and simulation output, respectively.

Given this system setup, the algorithm will compute the set of equations corresponding to predict and update, as seen in equations X through X. After predicting and correcting for the states of the system for time, the Kalman filter algorithm with then make future state predictions. It performs these predictions by slightly increasing the existing duty cycle D value by a small amount, recomputing the discrete state space system with this new value, and iterating through the prediction process again. It then slightly decreases the existing duty cycle D and again recomputes state space and prediction states. At this point, there is an estimation of states for time t=k given the existing duty cycle, as well as an estimation of future states for time given a slightly increased D, and slightly decreased D. These values will then be used in the MPC-Incremental Conductance algorithm.

**3.3 MPC-Incremental Conductance Design**

On every discrete timestep, the MPC-Incremental Conductance algorithm will receive the existing and future state estimates of the circuit from the Kalman filter. It will then use these values to calculate using the following equation:

(X)

Which is derived through circuit analysis of the converter both when the switch is on and off, as seen in figures X and X. The incremental conductance algorithm then uses and in the following flow chart in order to derive a desired reference current, .

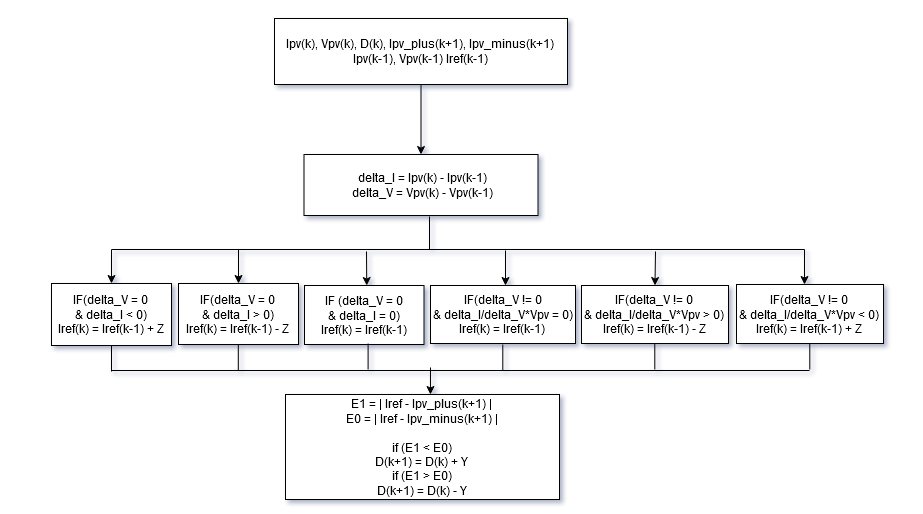


Figure X: MPC-Incremental Conductance Algorithm Flowchart

Where Z and Y are predetermined step values. On each discrete timestep, the variables from the Kalman filter (Ipv, Vpv, Ipv\_plus, Ipv\_minus) are received and the change in current and voltage is computed (delta\_I and delta\_v). The Incremental Conductance algorithm from the set of equations from X is then computed and a reference signal I\_ref is computed accordingly. The predicted values of Ipv\_plus and Ipv\_minus are compared to I\_ref and the duty cycle D is increased or decreased with the respect to the predicted duty cycle that produces the least error with respect to the reference. This duty cycle is applied to a PWM signal controlling the switches of the DC-DC converter.

**Chapter 4**

**Experiment**

**4.1 System Setup**

The following figure shows the high-level system model that must be implemented in simulation.

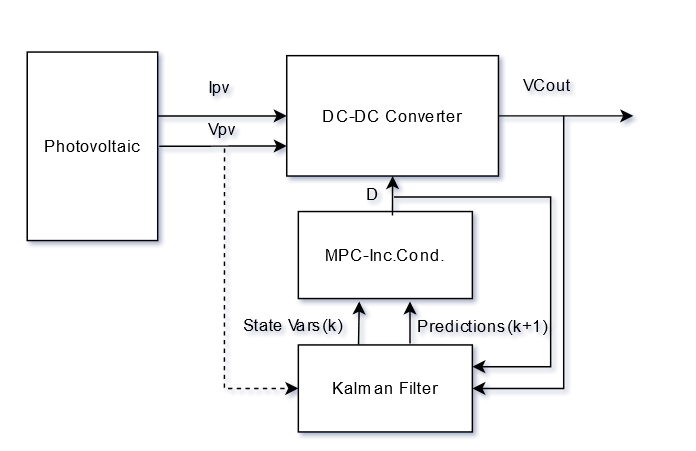


Figure X: Block Diagram of how each part the design interacts

**4.2 MATLAB Simulation**

**4.3 FPGA Hardware-in-the-Loop**

**Chapter 5**

**Results**

**5.1 MATLAB Simulation**

**5.2 FPGA Hardware in-the-Loop**

**Chapter 6**

**Conclusion**

**6.1 Discussion**

**6.2 Conclusion**

**6.3 Future Work**

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