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Effects of Load Dynamics on a Solar Photovoltaic Panel Fed Power Electronic System

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***Abstract* – One fundamental impact of change in energy mix is the increasing penetration of power electronic systems in the microgrid and main grid. For cascaded-power electronic converters, closely controlled downstream converters function as a constant energy load (CPL) to the upstream converters. A practical load in power electronic system consists of different combinations of constant power, impedance, voltage and current sources. This paper addresses the complex conduction and control of a power tracking system by the solar photovoltaic booster converter connected to a mixture of linear and non-linear stable power load .. The nonlinear modeling is shifted to nonlinearity in source, load, power and electronics. One striking observation is the absence of the commonly observed fast-scale period-doubling bifurcation reported previously in similar systems. Bifurcation diagrams have been plotted in terms of load parameters to indicate a panoramic view of system's behavior. Chaotic, DCM, slow-scale and negative impedance instability have been observed.**

Keywords* –** *Constant power load; stability analysis; slow-scale instability; negative impedance instability; dc microgrid; boost converter.**

INTRODUCTION

The primary impacts of change in energy mix are caused by the increasing penetration of renewable energy sources and various types of nonlinear and power-electronic loads in the main grid and microgrid. Installed capacity of renewable energy has seen a growth 36.5 GW in March 2014 to 74.8 GW in November 2019 contributing to 20% of India's total capacity [1]. Although the share of the Generation Mix rose from 5.6% to 7.8% over the same time owing to a lower power utilization factor. Solar power deployed has grown by an average of more than 6% each year, and by 26 GW in December 2018, from 2.6 GW in March 2014. With this increase, power electronic converter dynamics is becoming more and more pronounced in the distributed power system and microgrid dynamics, as they are required extensively for facilitating operations such as processing the obtained power and extracting maximum power from the renewable energy sources as well as for grid connection and supplying variety of loads. Cascaded power electronic converters help in maintaining desired point-of-load regulation [2].

Unfortunately tightly regulated downstream converters with one-to-one voltage-current characteristic as well as electric motor drive loads with one-to-one torque-speed characteristic behave as a constant power load (CPL) which exhibits negative impedance instability and tend to destabilize upstream converters.

Usually each converter is analysed, modeled, designed and controlled in an individual manner for a stand-alone operation while being supplied from a well regulated source and feeding a resistive or constant impedance load only [3]. However the dynamics of inter-connected and cascaded converters can be drastically different from the individual converters. Due to the complexity in modelling and simulating multi-converter power electronic systems, linearized averaged and reduced order model are employed instead of the switched nonlinear models. In a multi-converter power electronic system, two main types of loads can be seen which are constant voltage load and constant power load. Stability of such a system can be assured without implementing a stabilizing controller only when the power of the constant voltage load is greater than that of the constant power load [4]. Ref. [5] reported transient stability analysis in AC distribution system for various relative combinations of CPL and induction motor and concluded that CPL has the most destabilizing effects among all the load types.

Ref. [6] was first to report fast-scale period-doubling bifurcation where the same state repeats after two clock cycles in a solar (PV) array fed boost converter with resistive load by considering the nonlinearity of the nonlinear current source as well as the nonlinearity arising due to feedback controlled switches in boost converter. Stability of the period-1orbit was lost with variation in solar photocurrent, load resistance and current reference values. The study submitted later, in [7] the Solar PV Panel fed current mode operated boost converter, references to bipolar-doubling bifurcations with boundary crash with the values of solar photocurrent and battery voltage as a battery charger device. The bifurcation of the smooth and non-smooth phases of difference in ratio gain value was found for various rates of bus voltage[8]. Unlike the previous two works, input capacitance of the boost converter was taken into consideration.

Period-doubling bifurcation in a solar PV panel fed Ćuk converter with fractional open-circuit voltage maximum power-point tracking (MPPT) control and connected to constant impedance, voltage and current loads was observed [9]. Since solar irradiance and charge parameters frequently change unregulated and unexpectedly, it is important from a technically and architecture point of view, for stable free subharmonic operations, to specify critical parameter values of initial instability. Both fast-scale and slow-scale bifurcations in a similar system with resistive load, with increase in controller parameters, K_p and K_i respectively were reported also [10].

Regulated dc source fed boost converter is not globally stable under constant power loads [11]. Based on a large signal analysis with state feedback control, the authors observed two equilibrium points. The region of convergence did not include the origin and hence for such a system having a pure constant power load, the "start-up process" i.e., initial conditions play a vital role. A boost converter connected to a combination of resistive and CPL was stabilized by a feedback linearization method [12]. It would be pertinent to mention in this regard that a boost converter with a CPL is inherently an unstable system due to the existence of a RHS pole and zero. A plethora of passive and active methods exist in literature for stabilizing the negative impedance instability problem which reduces system damping, equivalent system resistance, stability margins and may results in high inrush current, limit cycle oscillation, voltage collapse in microgrid [13][14].

In a realistic multi-converter system, the load is not a pure load of any kind, be it constant power load, constant impedance load, constant voltage or constant current load. The load exists as a combination of the four basic types which varies from time to time. There remains a lacuna in present literature to ensure stability of power electronic converters and systems when they are feeding a mixture of linear and nonlinear loads instead of pure resistive load or pure CPL. Here stability is defined as the subharmonic and negative-impedance instability free behavior where same state repeats exactly after one switching clock cycle. In this study, CPL stabilization scheme has not been implemented to focus and explore the basic CPL dynamics. This paper is organised as follows: First, the power electronic system under investigation is described and the selection of this particular system is justified. Then, the dynamical behaviors exhibited by the system are explored. After discussing some crucial points based on the witnessed behavior concluding remarks are presented.

SYSTEM DESCRIPTION

A. Modeling of Solar PV Panel:

The solar PV panel has been implemented by the single diode model whose *v-i* transcendental equation is defined as a characteristic:

$$I_{ph} - I_o\{e^{\frac{q}{\gamma kT}(v_{pv}+i_{pv}R_S)} - 1\} - \frac{v_{pv} + i_{pv}R_s}{R_{sh}} = i_{pv} \quad (1)$$

By using Newton-Raphson method and by employing algorithms like Trust-region, Trust-region Dogleg, Levenberg-Marquardt etc. the above equation can be solved. Here $q = 1.6\times10^{-19}$ coulomb which is the charge of an electron, $k = 1.38\times10^{-23}$ J/K being the Boltzmann's constant, T is the absolute temperature, γ is diode ideality factor and I_o is saturation current of the diode.

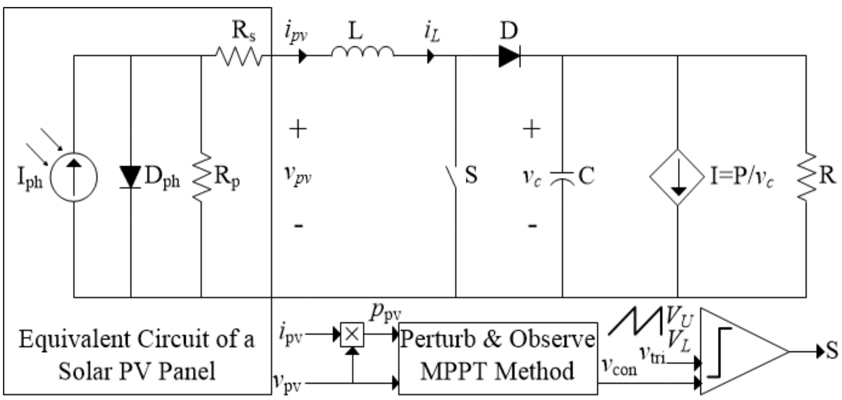


Fig. 1. Circuit diagram of the solar PV panel (modeled as a single diode model) fed boost converter supplying constant power and constant impedance load with P&O MPPT control method.

B. Power Circuit:

The dc-dc converters are used to process and produce full power from PV solar panels whose range depends on different factors[15]. Dc-dc converters are primarily used. The commonly used Boost converter has been designed to meet conditions like continuous input current characteristics which encourage accurate MPP monitoring, low cost and complexity, low passive part numbering, low input current ribbon, continuous input-output energy flow, equal output voltage polarity, low side and low cost drivers' circuit specifications, etc. However inability to track MPP efficiently under all irradiance, temperature, load conditions and all over the VI curve along with limited inclination angle constitutes some disadvantages of boost converter for this purpose.

Boost converter toggles between two LTI state-space subsystems based on the switching signal. The state-space equations describing the boost converter dynamics are defined below:

$$\frac{di_{pv}}{dt} = \frac{v_{pv}}{L} - \frac{v_c}{L}(1-d)$$
$$\frac{dv_c}{dt} = \frac{i_{pv}}{C}(1-d) - \frac{v_c}{RC} - \frac{P}{v_c C} \qquad (2)$$

which are solved numerically by the Runge-Kutta method. Here *d* is the duty cycle.

C. Control Circuit:

Extraction of maximum power from the solar photovoltaic panels is facilitated by various MPPT methods whose selection depends upon factors like ease of implementation, no. of sensors, ability to track true maxima in the presence of multiple local maxima caused by partial shading, cost, reliability, application requirement, convergence speed etc. [16]. The widely used perturb and observe (P&O) MPPT has been considered in this study. This control method is characterized by several advantages like low implementation complexity, possibility of both analog and digital implementation, no dependency upon the solar panel parameters and characteristics and a true MPPT mechanism. However, the requirements of voltage as well as the costly and bulky current sensor, inability to track the MPP in a rapidly varying environmental condition are some notable disadvantages of this method.

The clock frequency of this non autonomous device is calculated here by the frequency of the saw-carrier.

TABLE I

(TITLE: POWER AND CONTROL CIRCUIT PARAMETERS' NOMINAL VALUES)

Sl. No.	Power Circuit Parameters	Control Circuit Parameters
1.	Solar Photocurrent (I_{ph})= 1A	V_L = 0V
2.	Inductor (L) = 3 mH	V_U = 1V
3.	Capacitor (C) = 20 µF	Clock Frequency (*f*) = 10 kHz

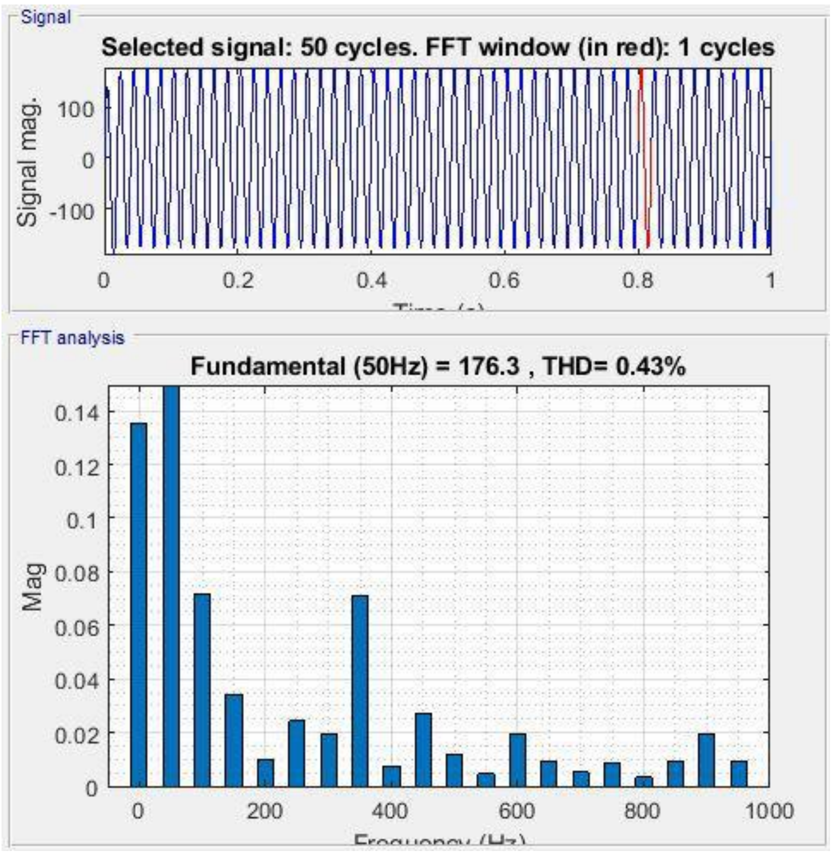
DYNAMICAL BEHAVIOR OF THE SYSTEM

Now the nonlinear switched model will be simulated to give a glimpse of the possible dynamical behaviors and in the exact simulation model all the nonlinearities will be considered and modeled which arises due to:

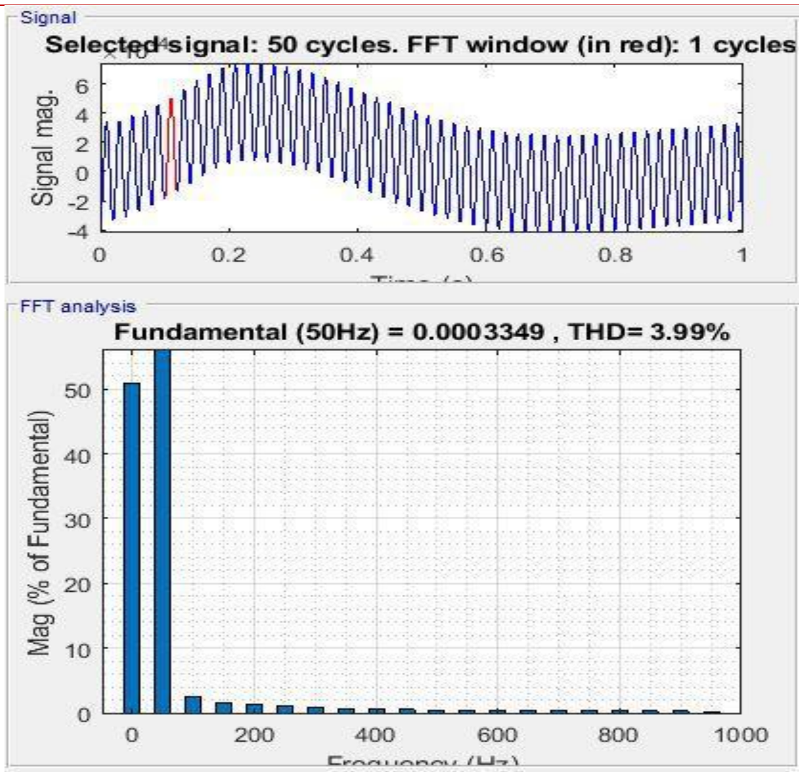
a) Nonlinear current source
b) Nonlinear feedback controlled boost converter
c) Nonlinear constant power load
d) Nonlinear P&O MPPT controller.

Since, the objective of this work is to explore the effect of load dynamics on the overall system, the case of constant power load and constant impedance (resistive) load will be dealt with individually while the solar photocurrent is assumed to be constant. After that the combined effect of both constant power and impedance load will be considered.

At first, the system with only resistive load is investigated. For lower values of resistance, stable period-1 behavior with low THD can be seen as shown in Fig. 2. (a) and (b) for R= 15Ω. However with increase of resistance, slow scale oscillations set in. The wideband frequency spectrum with slightly higher THD can be termed as a type of chaotic behavior for R=50Ω.



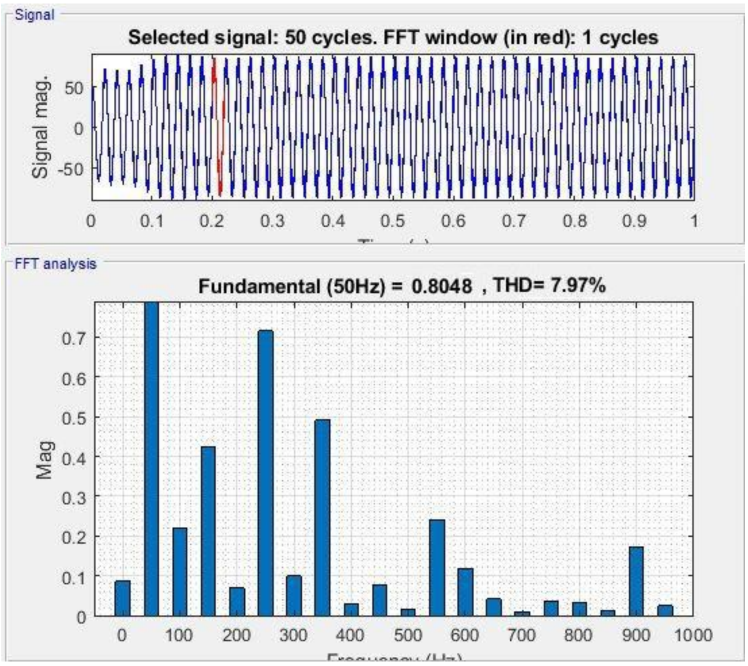
(a)



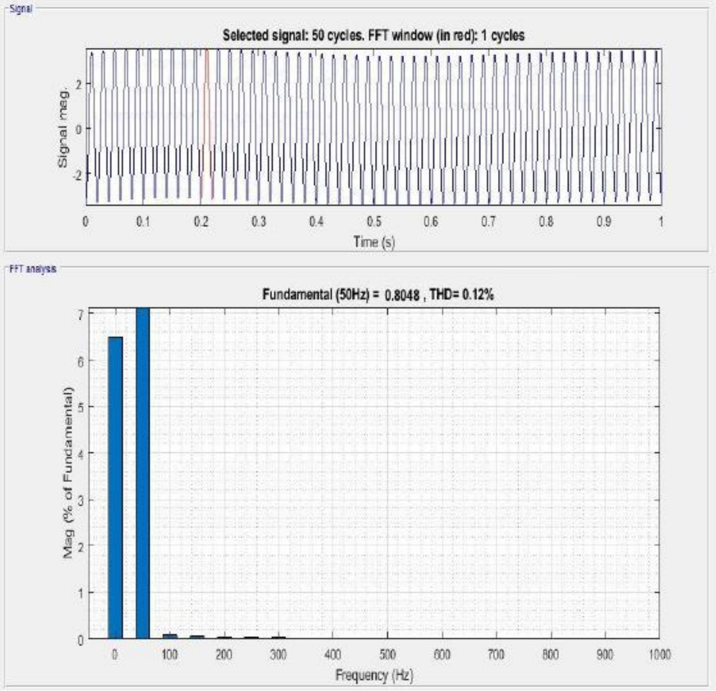
(b)

Fig. 2. (a) Inductor current (i_L) waveform and FFT plot for R= 15 Ω; (b) i_L waveform and frequency spectrum for R= 50 Ω.

The machine dynamics are then studied with a steady power load only. The machine shows erratic actions at low P values. In this system, the maximum power that can be extracted from the solar PV panels is 12.9 W. From 11 W to 12.8 W, stable period-1 behavior can be witnessed with low THD. Hence a critical condition arises if the load demand exceeds the supply demand and the system collapses with load current→∞ and load voltage→0 in an exponential fashion.



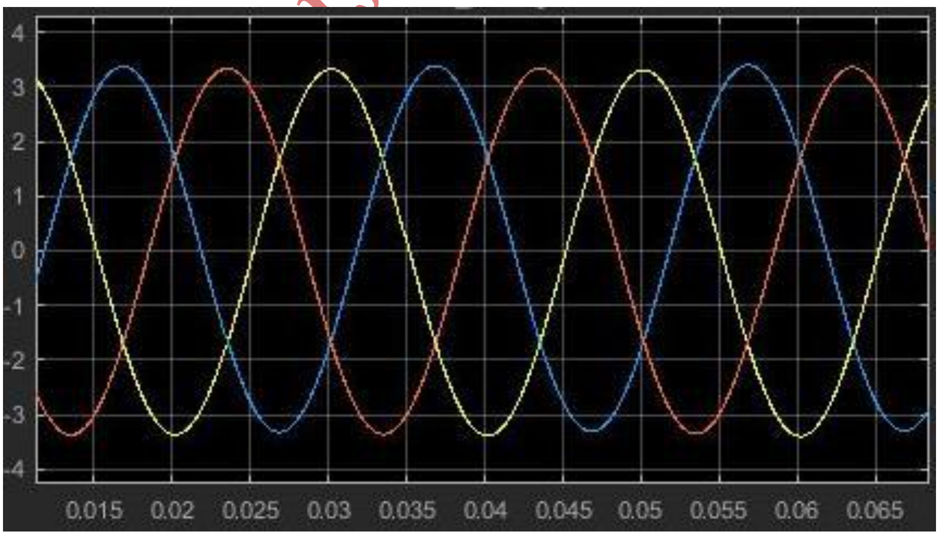
(a)



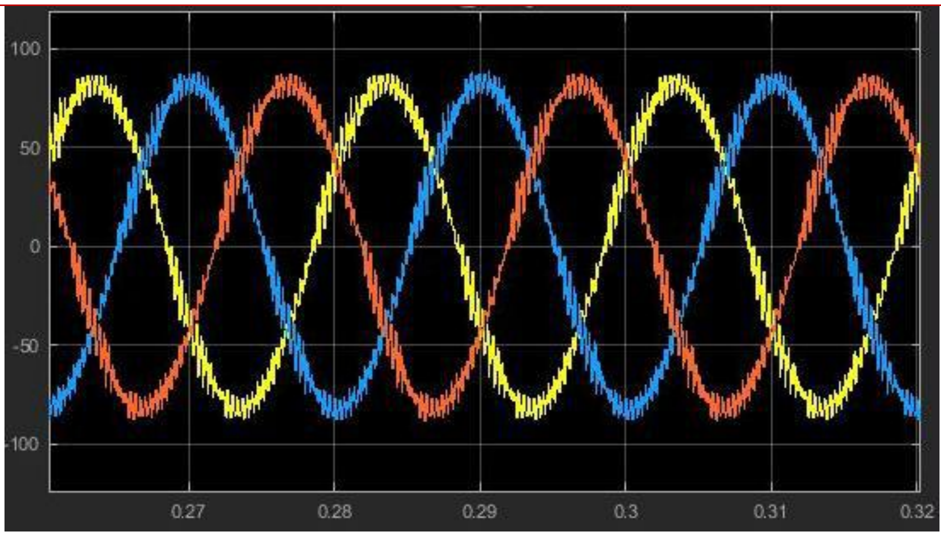
(b)

Fig. 3. (a). Inductor current (iL) waveform and FFT plot for P= 4W; (b) iL waveform and frequency spectrum for P= 11W.

The bifurcation diagrams are now built for a panorama over a broad space parameter of the system's complex behavior, as seen in fig. 4. The frequency of inductor current is calculated at the beginning of each clock period while the device is in steady state. Stable period-1 behavior with resistive load is observed to allow for very limited amplitude slow-scaling with enhanced load power. For low values of CPL, chaotic behavior with relatively higher THD, DCM behavior and behavior with long transient condition have been observed.



(a)



(b)

Fig. 4. (a). Diagram for bifurcation R as a criterion for bifurcation.
(b) Bifurcation graph with P as parameter for bifurcation.

Fig. 5. Shows the complete dynamical behavior where the solar PV panel is supplying a mixed load of CPL and parallel resistive load (R). CPL has been given a parametric swing while R is kept constant. THD decreases with increasing P and a slow-scale oscillation cycle with minor amplitude has been detected. Beyond P=12.1W the system collapses with exponential load current rise.

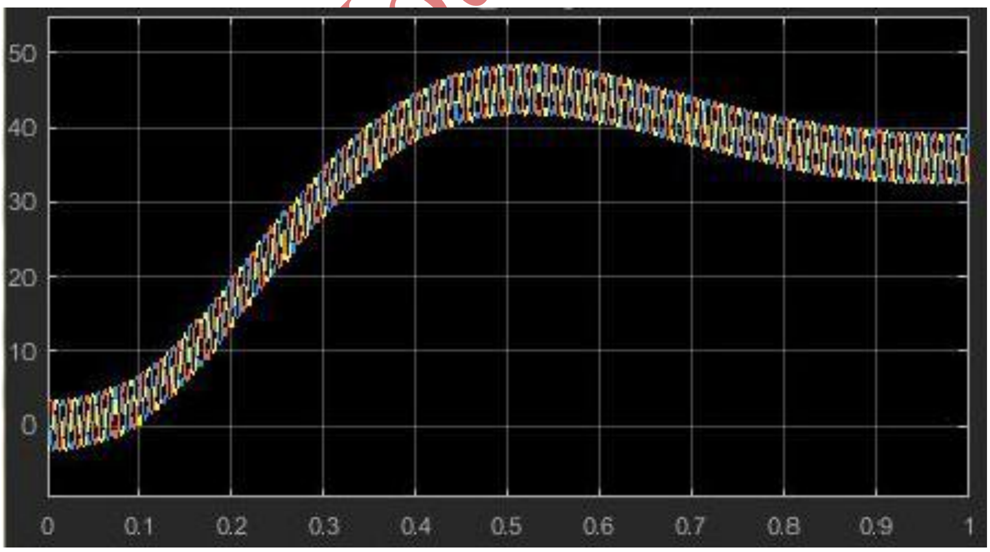


Fig. 5. Diagram for bifurcation with constant power (P) as the bifurcation parameter for R=300 Ω

DISCUSSION

Period-doubling bifurcation has been reported so far as the predominant phenomenon in solar panel fed boost converter. In the sense of the operation of linear controls, Ref.[6], [7] takes into account the solar panel nonlinearity, along with the non-linearity of the boost converter. The authors claimed that the relationship between these two forms of non-linearities expanded the stable field of operation. Ref. [8] disputed previous author's and claimed that little or no effect on the period-doubling forcing was the non-linearity of the solar panel PV and the MPPT. This claim was backed by the authors' reasoning that the MPPT controller is slower than the converter 's quickly shifting dynamics. With the Solar Photovoltaic Wall, which is fed by a linear fractional MPPT voltage transmitter, and the fed linear charges to converter, time replication of bifurcations has again mainly been observed[9][10].

In the present system under investigation, in addition to the source and switching converter nonlinearity, the nonlinearity of the load and MPPT controller have been considered. The argument made by the authors of reference [8] contradicts with the observations in this work. The behavior has been devoid of fast-scale instabilities which had been witnessed in similar systems till date and that may be attributed to the nonlinear P&O MPPT controller which is a dynamic and true MPPT controller. Slow-scale, chaotic behavior along with DCM behavior were witnessed. Hence, the incorporation of the additional nonlinearities of the switched nonlinear modeling of this practical and widely used system has thrown some insights into its dynamics.

CONCLUSION

Solar PV panel boost converter dynamics have been investigated by constructing an exact switched nonlinear model and taking the non-linearities of the source, power, switching and controller. The absence of fast-scale period-doubling bifurcation in this widely used practical system is notable. Chaotic, DCM, slow-scale and negative-impedance instability have been witnessed. Future scope of work involves extensive analysis, corroboration of simulation results with analytical and hardware results where the combination all the four basic linear and nonlinear load types as well as other practical nonlinear loads will be considered.

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