Treball Final De Master

Master Universitari en Automatica I Robotica

Passivity-based control of multi-terminal HVDC systems under control saturation constraints

MEMORY

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Chapter 1

Introduction

1.1 Motivation

The growing demand of energy has encouraged the UE to find solutions about reducing energy consumption. This isn't the only way to solve the problem. The UE have set a target of 20% share of energy from renewable source in the gross final consumption of energy of the European Community by 2020 [1]. The aim is to reduce dependence on fossil fuels from countries with unstable political situation [2] and to reduce the green house emission, in accord with the Kyoto Protocol.

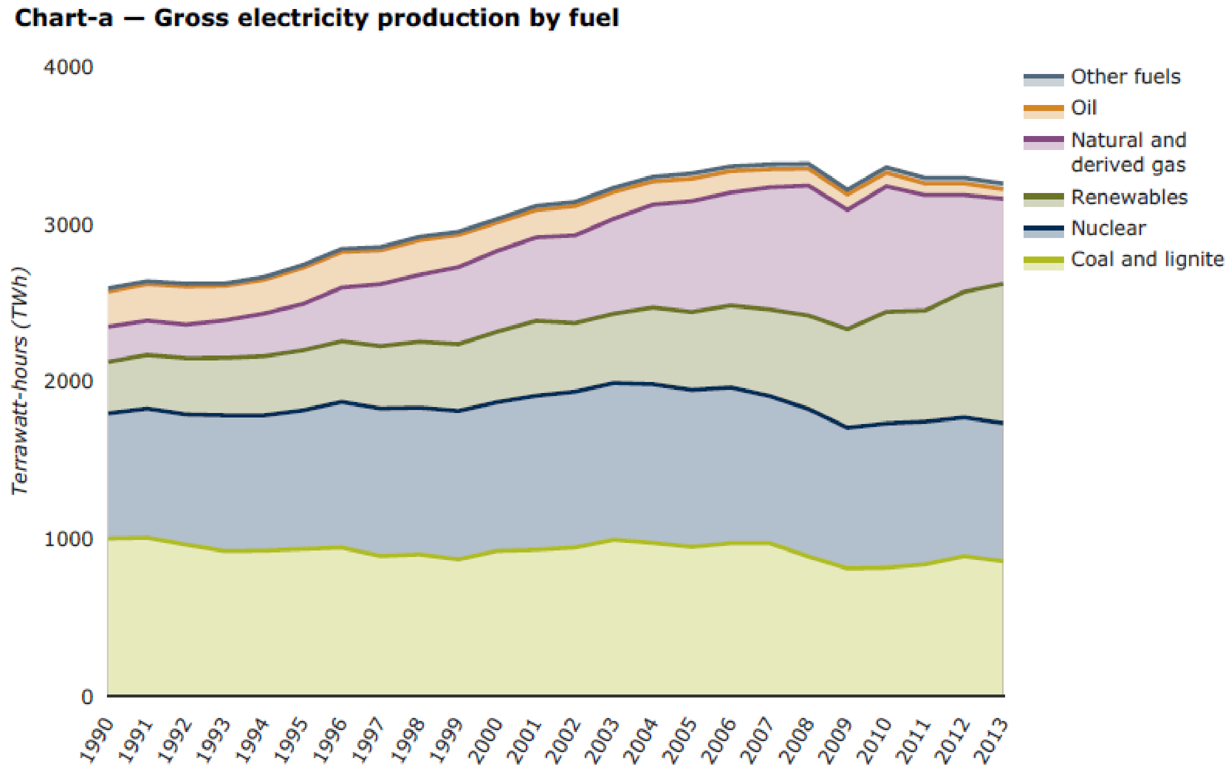
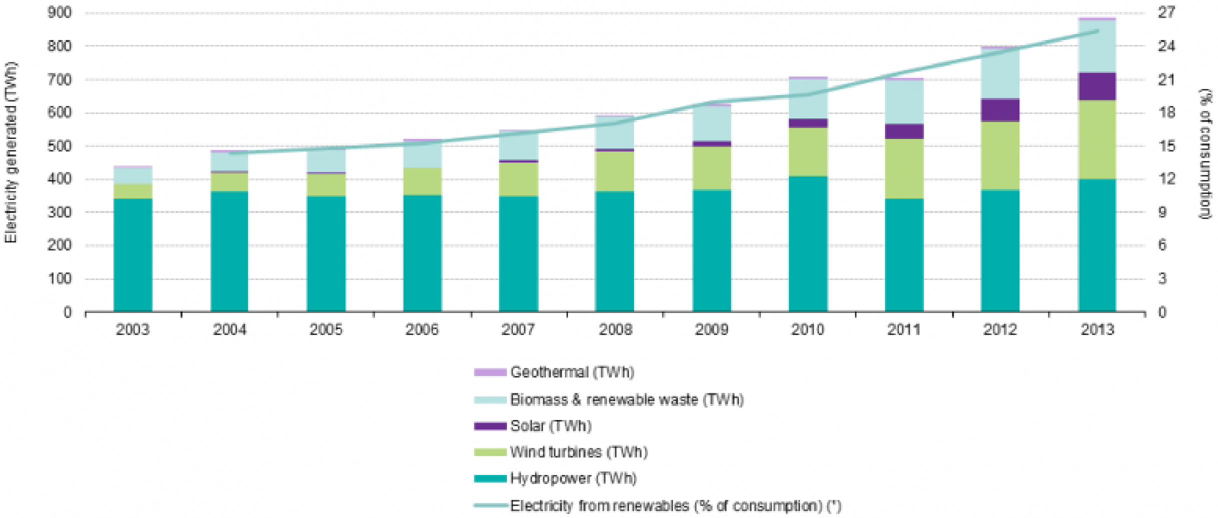


Figure 1.1:

According to the statics of EA, between 1990 and 2013, gross electricity generation in the EU-28 increased by 26%, at an average rate of 1% per year. Since 2005, a small decrease of 0.3% per year was observed[3]. In 2013 the production of the all energy, was composed to 27% by the renewable energy (compared to 13% in 1990) [4],Figure 1.1. Among the different renewable source of energy in the EU, wind power has shown the largest growth and penetration during the last decade and it is expected to increase significantly in the near future.



(¹) 2003: not available.
Source: Eurostat (online data codes: nrg_105a and tsdcc330)

Figure 1.2:

Between the source of renewable energy, the wind source represent the 9% (on 27%). Only the Hydropower has a higher percentual (12%). The improvement of wind power have few reasons. The Wind power today came from on-shore and off-shore plants. The On-shore power represent a mature tecnology, but the expansion presented some problems expecially for the resistance by some members of the public and planning procedures. For this reason the off-shore tecnologies was increase. In the first place the power that could be extracted from the wind is proportional to the cube of the wind, therefore the higher speeds at open sea might improve the wind farm's capacity factor and bring larger energy outputs. Also the wind is less turbolent and doesn't increasi with the height as in land location, wich allows the use of shorter towers. Thirdly, the open sesa provides major continuous asear implement large-scale wind farms. This is especially problematics in country with densely populated areas, high penetration of wind power or where public resistance constantly delays.[5]

1.2 HVDC Power Trasmission System

There are actualy two technologies for electricity trasmission, High Voltage Alternating Current (HVAC) and High Voltage Direct Current (HVDC). The first one has been in practice for generating, trasmitting and distributing the electricity almost every on- and offshore wind farm. Medium Voltage standards of 33KV are widely used for power trasmission is a single cable up to 30-40 MW. On the other hand HVDC has been used to support and complement AC network in different application. The interesting part is that despite its little use, this technology offers several technical advantages over HVAC. With it, easy and fast control of active and reactive power is possible as well as voltage and current support to the surrounding AC grid.[6]. It protected the wind farm acting as a barrier against grid failures and vice versa, which also reduce the size of transformers and othe compoents in the turbine [7] and more important, losses in HVDC system are considerable smaller for higher power rating and long trasmission distances. The problem is that the HVDC electronics components are more expansive than HVAC. HVDC comprises two different technologies. The first one is called Line Commutated Converter (LCC), used for bulk power trasmission over incredibility long distance, and the second one si called Voltage Source Converter (VSC). VSC offers certain advantages over LCC systems like more controllability of active and reactive power, indipendence from external voltage sources and faster control system [8]. On the other hand, it's power rating is limited to c.a 1GW, the losses are higher than in LCC and there might be contraints in the supply of subsea cables [9]

1.3 Report structure

The goal of thesis is to show how the network evolve when there are different intial condition and different control action. The thesis is developed in 5 chapter:

- Chapter 1: Interest of the UE about the renewable energy: the offshore wind plants
- Chapter 2: Introduction in the VSC-HVDC network with Passivity Based Control
- Chapter 3: Evolution of the network when the reference is out the admissibility region: case of P control
- Chapter 4: Evolution of the network with PI control: difference between the different kind of control
- Chapter 5: Conclusion

Chapter 2

Multi Terminal VSC-HVDC Trasmission System

2.1 Description

The Multi-Terminal VSC-HVDC network is analyzed, Fig 2.1 . This network is composed by 8 node. There are two different kind of node: Power Plants (square) and Grid Side (circle) [10]. The first represent the offshore plants for the wind power generation. The second represent the power grid side station. The connection between this nodes is realized with a DC grid. The connection between nodes and network is done trought VSC converters, that represent the DC/AC converter and viceversa.

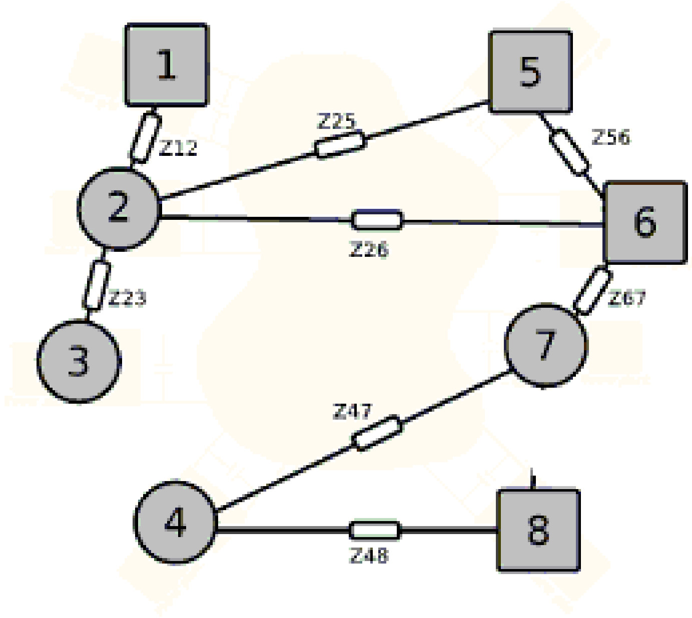


Figure 2.1: M-HVDC network: power plants (square), grid side station (circle)

The VSC converters, modelled as a capacitor in parallel with a current source, have the aim to set the desire votlage in the DC capacitor. This is possible with the application of the source current that represent the control action. The control of the network is an hierarchical control where the regolation of the voltage of the DC capacitor represent the primary level [11]. The secondary level is a supervisor algorithm that set the required voltage. The lower level providing to establishing the politcy to exctract and inject the required current from/to the capacitor. The primary and lower control belongs to the decentralized controller, while the secondary level represent a way to obteneid the voltage for the capacitor. The voltages of each nodes represent the equilibria of network. The goal of the decentralized control is to keep the network HVDC stable.

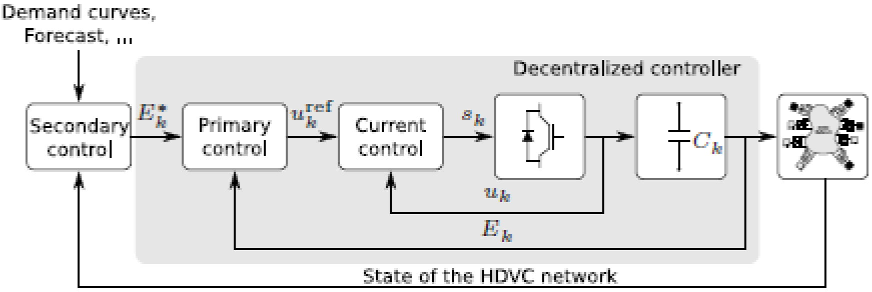


Figure 2.2: Control scheme

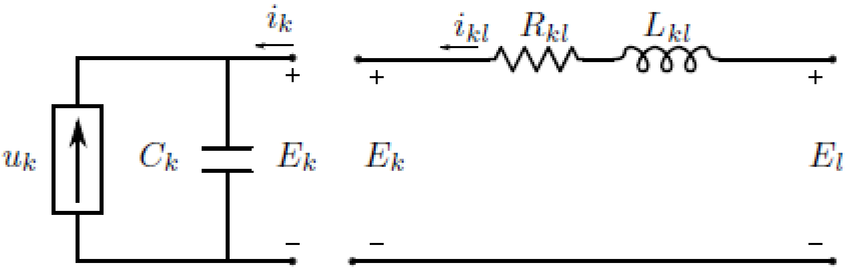


Figure 2.3: Equivalent circuit: VSC (left), Line (right)

2.2 Mathematical model

For obteined the mathematical equation that exploit the evolution of the system are applied the KVL and KVC in the circuit that represent the VSC and the line between the nodes. The application of KCL give this result for each nodes:

$$C_k\frac{dE_k}{dt} = u_k(E_k) + i_k \tag{2.1}$$

Where $C_k$represent the capacity, $E_k$represent the voltage of the Capacitor, u_k is the current of the power converter and i_k is the current in the capacitor. It's equal to:

$$i_k = \sum a_{kl} i_{kl} \tag{2.2}$$

where $i_{kl}$is the current that flow to node k from l and a_{kl} is equal to:

$$a_{kl} = \begin{cases} 1 & if \ \ k \ \ is \ \ connected \quad to \quad l \\ 0 & if \ \ k \ \ isn't \ \ connected \quad to \quad l \end{cases} \tag{2.3}$$

With the KVL the dinamycs of the lines is given by:

$$E_l = E_k + R_{kl}i_{kl} + L_{kl}\frac{di_{kl}}{dt} \tag{2.4}$$

If i represent the vector of the currents $i = (i_{kl}) \in R^m$, where $m \in R^{\mathbb{N}}$ is the total number of the trasmission and $n \in R^{\mathbb{N}}$is the number of nodes, the equation (1) and (4) can be write in matrix form:

$$C\frac{dE}{dt} = -Ai + u(E) \tag{2.5}$$

$$L\frac{di}{dt} = -Ri + A^tE \tag{2.6}$$

where $E = (E_i) \in R^n$, $u = (u_i) \in R^n$, $C = diag(C_i) \in R^{nxn}$, $A = (A_{jk}) \in R^{nxm}$ who represent the incidence matrix

$$A_{jk} = \begin{cases} 1 & if \quad line \quad j \quad connects \quad from \quad node \quad k \\ -1 & if \quad line \quad j \quad connects \quad to \quad node \quad k \\ 0 & otherwise \end{cases}$$

$L = diag(L_{kl}) \in R^{nxm}$, $R = diag(R_{kl}) \in R^{nxm}$ are the induttance and resistance matrices. With this result, the equation who describe the evolution of the system is:

$$\frac{d}{dt}\begin{pmatrix} E \\ i \end{pmatrix} = \begin{pmatrix} 0_n & -C^{-1}A \\ L^{-1}A^T & -L^{-1}R \end{pmatrix}\begin{pmatrix} E \\ i \end{pmatrix} + \begin{pmatrix} C^{-1} \\ 0_{mxn} \end{pmatrix} u \tag{2.7}$$

After this, the control that is applied is a Passivity Based Control. Is necessary to pass the system in the Port-Hamiltonian framework. With capacitor charge and inductor fluxes

$$q = CE \in R^n \tag{2.8}$$

$$\lambda = Li \in R^m \tag{2.9}$$

it's possible to obtain the Port-Hamiltonian system [12]:

$$\begin{pmatrix} \dot{q} \\ \dot{\lambda} \end{pmatrix} = \begin{pmatrix} 0_n & -A \\ A^T & -R \end{pmatrix} \frac{\partial H}{\partial x} + \begin{pmatrix} I_n \\ 0_{mxn} \end{pmatrix} u \tag{2.10}$$

$I_n$is the identity matrix and

$$H(q, \lambda) = \frac{1}{2} q^T C^{-1} q + \frac{1}{2} \lambda^T L^{-1} \lambda \tag{2.11}$$

standing for the total Hamiltonian function.

The equilibrium point that are obtained from the equation in Port-Hamiltonian framework are the solution of the equation:

$$A^T C^{-1} q^* - R L^{-1} \lambda^* = 0_m \tag{2.12}$$

If E^*represent the desired value of the voltage for the node, the respective charge and flux equilibria are:

$$\begin{gathered} q^* = C E^* \\ \lambda^* = L R^{-1} A^T E^* \end{gathered} \tag{2.13}$$

The application of the control law, globally stabilized the system. This result is proved by the pH model, becouse the function is look like an Lyapunov function. The control action is:

$$u^s = A R^{-1} A^T E^* \tag{2.14}$$

globally stabilizes the M-HVDC at the desired voltage E^* and current $i^* = R^{-1} A^T E^*$.

The other control law:

$$u^d = u^s - K(E - E^*) \tag{2.15}$$

with $K = (K_k) \in R^{nxn}$ and $K_k > 0 \vee k$, globally asimptothic stabylized the M-HVDC network at the voltage $E^*$with current equal to $i^* = R^{-1} A^T E^*$.

The other control action used in this thesis is the PI control:

$$u^{PI} = A R^{-1} A^T E^* - K(E - E^*) + K_i \int (E - E^*) dt \tag{2.16}$$

Where $K_i$represent the diagonal matrix of the integral control.

This represent the PassivityBasedControl, but in the real application, this control doesn't have saturation. In this way the value of the voltage and current can obtain values dangerous for the network. It's necessary to define maximum and minimum value of the power for each node and with the control action ensure that the voltage and current stay into the admissibility region. In that way the control action become:

$$u_k = f(u_k^d) = sat_{kI} \left(\frac{sat_{kP}(u_k^d E_k)}{E_k} \right) \tag{2.17}$$

where the saturation function is defined by:

$$sat_{kI}\left(\cdot\right) = \begin{cases} I_k^{max}\; if & \left(\cdot\right) > I_k^{max} \\ \left(\cdot\right)\; if & I_k^{min} \leq \left(\cdot\right) \leq I_k^{max} \\ I_k^{min}\; if & I_k^{min} > \left(\cdot\right) \end{cases} \tag{2.18}$$

$$sat_{kP}(\cdot) = \begin{cases} P_{kI}^{max} \quad if & \left(\cdot\right) > P_{kI}^{max} \\ \left(\cdot\right) \quad if & P_{kC}^{min} \leq \left(\cdot\right) \leq P_{kI}^{max} \\ P_{kC}^{max} \quad if & P_{kC}^{min} > \left(\cdot\right) \end{cases} \tag{2.19}$$

with $I_k^{max}, P_{kI}^{max} > 0$ and $I_k^{min}, P_{kC}^{min} \leq 0$.

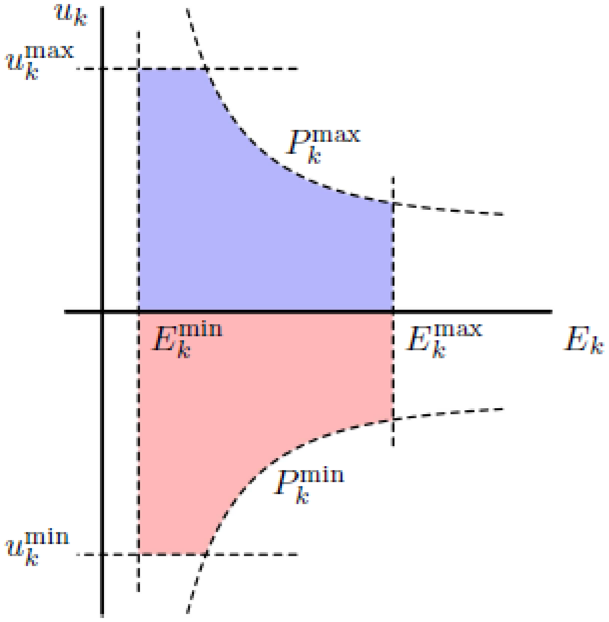


Figure 2.4: Admissibility region

2.3 Experiment

The idea of this work starts from the [14], where is studied the application of control (15) on the network in which the nodes have intial conditions into the admissibility regions. The application of different controls on the M-HVDC network, Fig ,where the nodes have initial conditions that are out the admissiblity region, are object of study in this thesis. Recall once again that the goal of the control on the network is to regulate the voltage at each node in order to set a desired voltage in different periods. The aim of thesis is to show how the variations of some particular nodes's initial condition can influence the evolution of the variables state of the other nodes in the network and whether this change allows to reach their reference of voltage. Furthrmore, with the same variation of inital conditions, are evaluated the apply of differents kind of control. The studied network , has 8 connection lines and 8 nodes are divided in two categories: PP, represent with the square in the figure;

GS, represent with circle. For each node all physic parameters are defined , Table 2.1, while in Table 2.2 there are the physical parameters of the connection lines. In the Table 2.1 there are different columns and each of theme represents explain some feature of the nodes. For example the P_k^{max} and u_k^{max} represent the maximum power and maximum current of the control, which define the admissibility region of the nodes, Fig 2.4. The K_k columns show the value of the diagonal matrix's control. The values of the columns E_{k1}^*, E_{k2}^* and E_{k3}^* suggest the referements of each node in the three different periods. The first period, starts from 0 to 0.5 seconds; the second from the end of the first until 1 second; the last period starts from 1 second to 1.5 seconds. Those referements are the desired voltages, according to the period, of each node. $E_k(0)$ represent the vector of initial conditions of some nodes such as Node 1, 2 and 8. In the other cases, the intial conditions are the same of the first reference (E_{k1}^*).These valeu are obteined from the equation (14), where, fixing the value of the control current, is possible to obtein the value of the voltage that is out of the admissibility region. The choice of those nodes is based on their own nature, becouse the Node 1 and 8 have only one connection, but only the first node is connected to an Hub. The node 2 is an Hub for the network, becouse it has a lot of connections. The thesis analyzes how the variations of these nodes's initial condition lead to some changes in the other nodes. In particular, what happen to the furthest and the closest nodes when the initial conditions of nodes with poor or more connection connections change. To explain this variations, in Chapter 3 and 4 there are different kind of graphs: the evolutions of the state varaibles of the node where are the changes of the initial conditions; the evolutions of the state variables of the other nodes; the behaviour of the voltages of each node in the first period; finally, its behaviour in all periods. These graphs show the variations that occur in the nodes when there are different intitial conditions in one of them. In particular, the voltage's graph show if the voltages of nodes reach the referements of the periods. Furthermore, the variables state's graph explain how the change of initial condition lead to variations in the equlibrium points of the other nodes. The last kind of graphs are a cartesian plane in which the x-axes represents the voltage's capacitor of the node and the y-axes represent the sum of the current lines that enter and exit to the node. In particular, the chapter 3 shows the results for the different values of the prportional action control. These values are obtained by an experimental base and each of them explains different system's behaviors. In particular, three are the point examined: the first is the case study [14], the second is the value for which at the bottom of this, the voltage in the third period loses the oscillatory way; the last value is obtained by the application of the Ziegler-Nicholson'rules,that normally are used on the PI control and in this case they are chosen to obtain simulations and to make possible a comparison with the PI control. instead, the main character of the 4 chapter is the system's evolution related to a PI control. There are also the comparisons between the two different controls. In the end, the thesis explains what happen to the voltage of a node when the proportional and integral gains change.

Node 1	Node 2	Node 8
414600 V	412485 V	423000 V
413800 V	411600 V	417000 V
413000 V	410531 V	411000 V
406200 V	402000 V	387000 V
	400130 V	
	398770 V	

Table 2.2: Simulation parameters: Initial condition of Node 1, 2 and 8

Node	Type	C_k	P_k^{max}	u_k^{max}	K_k	$E_k(0)$	E_{k1}^*	E_{k2}^*	E_{k3}^*
N1	PP	$75\mu F$	300 MW	1.0 kA	0.75	Tab 2.2	412 kV	399 kV	405 kV
N2	GS	$75\mu F$	600 MW	1.5 kA	0.75	Tab 2.2	407 kV	398 kV	398kV
N3	GS	$75\mu F$	400 MW	1.3 kA	0.75	402 Kv	402 kV	400 kV	390 kV
N4	GS	$75\mu F$	400 MW	1.5 kA	0.75	390 Kv	390 kV	420 kV	420 kV
N5	PP	$75\mu F$	350 MW	1.2 kA	0.75	405 Kv	405 kV	410 kV	410 kV
N6	PP	$75\mu F$	500 MW	1.4 kA	0.75	403 Kv	403 kV	410 kV	410 kV
N7	GS	$75\mu F$	600 MW	1.5 kA	0.75	399 Kv	399 kV	405 kV	405 kV
N8	PP	$75\mu F$	200 MW	1.0 kA	0.75	Tab 2.2	405 kV	423 kV	423 kV

Table 2.1: Simulation parameters: node values

Line	L12	L23	L25	L26
Lenght [km]	40	30	100	300
$I_{kl}(0)$ [kA]	0.62	0.83	0.10	0.07
Line	L47	L48	L56	L67
Lenght [km]	175	150	50	30
$I_{kl}(0)$	-0.26	-0.49	0.20	0.67

Table 2.3: Simulation parameters: line values

Chapter 3

P Control

The objective of this dissertation is to show the consequential variations of a phase plane of a single node due to changes in voltage and current, taking into consideration that changes in a node are likely to affect other nodes as well. Hence, the aim of this research is to show how equilibrium points react when initial conditions vary. A variation in initial conditions translates to a shift outside from the admissibility region, which is bounded by the limits given by the action control. The action control limits the current and power within a range, in order to obtain the desired voltage in each node. To begin with, the evolution of the system has to be monitored when the value of the proportional control is determined. This leads to reach the desired voltage for each node. Depending on where the change in initial conditions occur, the system reacts in a different way. Changes may take place in nodes with various connections or in nodes with fewer connections. In second stand, this dissertation will analyze the system's evolution when the proportional value of the action control changes. Consequentially, the possible outcomes of the system will be examined, when the PI control is in use. Moreover, a comparison between the two different types of control will be -made, in order to assess which one is ideal for this type of analysis. The evolution of the system has been monitored and divided in three time lapses of 0.5 seconds each. For each time lapse, the nodes have different references. However, the research that has been made shows the changes in references just for the first time lapse, which extends from zero to 0.5 seconds.

3.1 Fixed value of proportional gain

In this section, the evolution of the system will be analyzed when the value of the diagonal matrix's proportional control is fixed to 0.75.

3.1.1 Node with poor connection

The nodes that have been taken into consideration are the ones with few connections. Nodes n1 and n8 are the ones falling into this category because they just have one direct connection with another node, laying on the borders of the network. The objective of this study is to show how changes in a node affects not only the node itself, but the other ones in particular.

3.1.1.1 Node 1

This node has only one direct connection with another node, n2. In this case, the current in the connected graph shifts from node n1 to node n2. Only in this case, the Admissibility region is the same for the space state, becouse the current line is the same of the source current in the Node 1. The research begins in a state given that the initial condition is outside the admissibility region. This region is defined in the state space where the x-axis represents the voltage of the capacitor and the y-axis represents the sum of the current line. Firstly, the evolution of node n1 will be observed when changes occur in node n 1 itself and consequently how the other nodes are affected. If the value of the voltage lays between 407000 and 412810, the node stays in equilibrium, hence there are no significant variations in the state variables. This range represents a state of equilibrium for the system, since there are no variations in the space state. The system behaves differently if the reference is either greater than 412810 or lower than 407000. If the initial voltage is over 412810, the state variables lie between the admissibility region. Consequentially, the system will converge to an equilibrium point that lies on a line that represents the maximum power level of the node. The voltage value of the equilibrium point will be lower as the distance from the admissibility region increases. The system oscillates around the equilibrium point like foci. The voltage will have a deeper under elongation in the transitory and the transitory will be longer as the distance of the initial condition from the admissibility region increases. Any change in the reference of node n1 will affect the other nodes, particularly node n2, since there is a direct connection between nodes n1 and n2. In this case, node n2 will react in the same way as node n1. Nodes n 3, 5, 6 and 7 are affected by variations of node n1. The higher the distance from node n1, lower will be the influence on the nodes. Nodes n4 and 8 will not be affected by a change in the initial conditions for node n1, as there are minimum three nodes between them. On the other hand, if the voltage is lower than 407000, the voltage of node n1 will witness an upper elongation. Consequentially, node n2 will behave similarly to node n1. Nodes n 3, 5, 6, and 7 will have a voltage slightly higher than the reference value. When the voltage value of node n1 is equal to 398000, node n3 will undergo a persistent oscillation. Nodes n 5 and 6 will behave in the same way when the voltage value of node n1 is 390800 and 390300, respectively. This behavior will be different from the other case because there are no oscillations in the nodes, independently from the values of the voltage on node n1.

The Figure 3.1 shows the evolution of the voltage and current. All initial points are out of the admissibility region, but three of these are up of that region and one is under the admissibility region. If the initial condition is into the admissibility region, there isn't movement in the state space. .

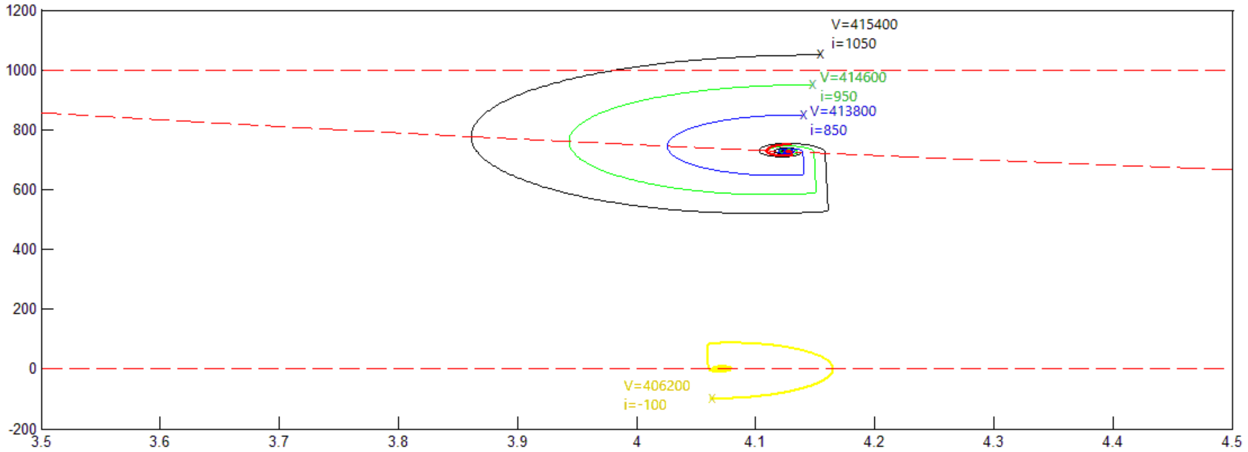


Figure 3.1: Evolution of state variables of Node 1

The Figure 3.2 is a zoom of the equilibrium points. The equilibrium points are different because they depend by the initial conditions. Lower is the value of the voltage of initial point, higher is the voltage of the equilibrium point.

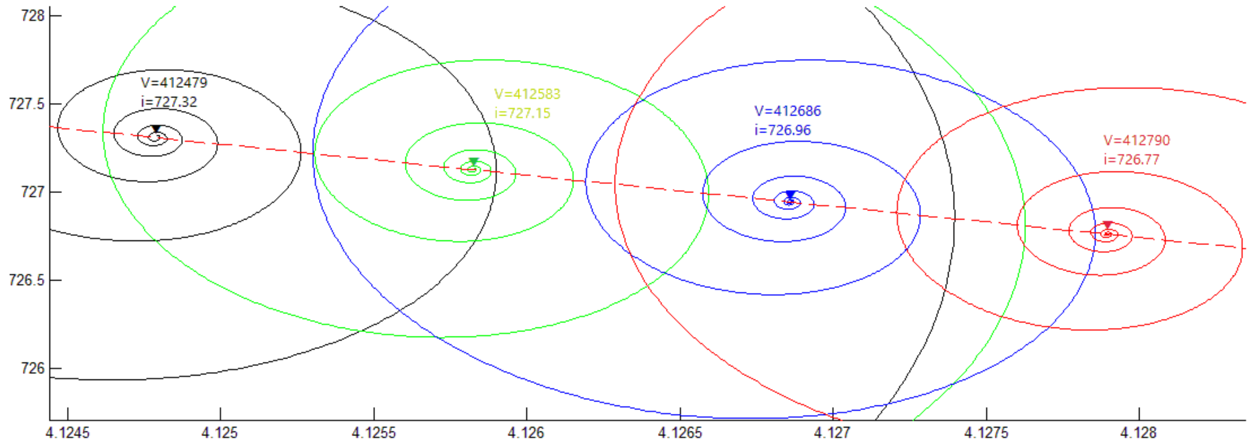


Figure 3.2: Equilibrium point of Node 1

The transitory of the evolution of the voltage present a deeper under elongation if the value of initial point is more far from the admissibility region. The black line, in Figure 3.3, represent the evolution when the value of the reference of voltage is equal to 415400. This value is further from the admissibility region.

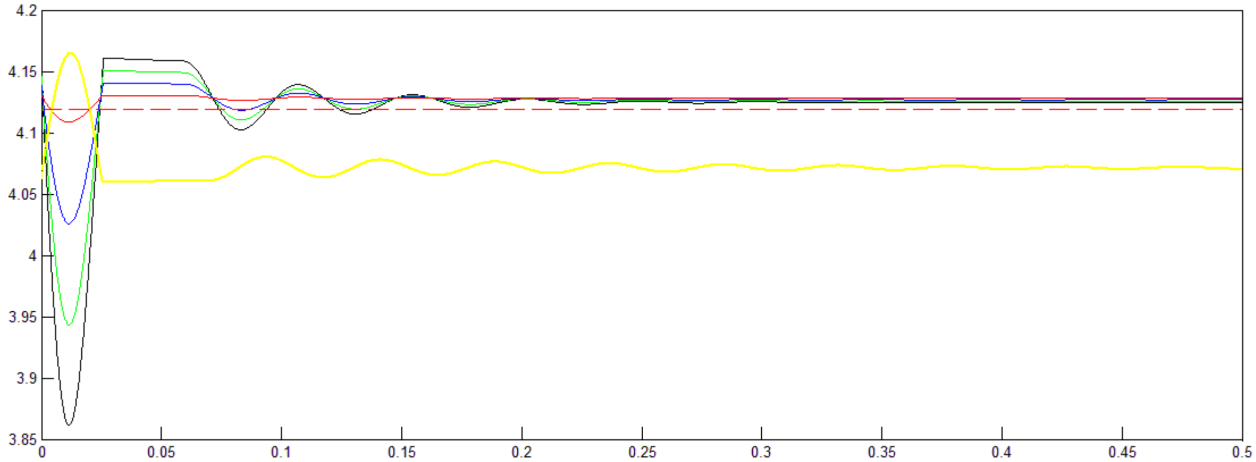


Figure 3.3: Voltages of Node 1 in the first period with different references

The yellow line represent the trend of voltage when the reference is under the admissibility region.

The voltage after 0.5 seconds has the same behavior. This behavior doesn't depend by the value of the first reference. In the second and third period there aren't some variation.

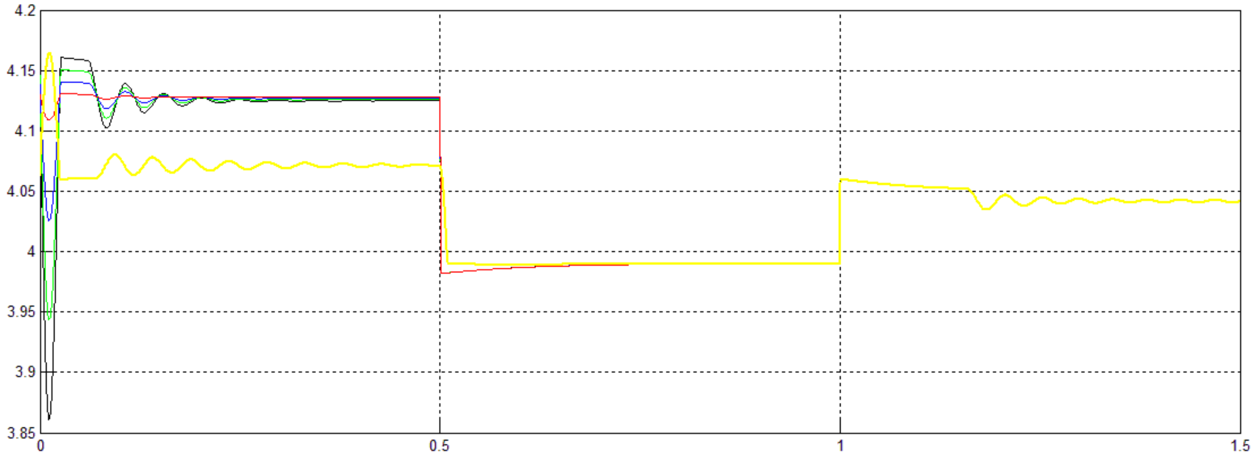


Figure 3.4: Voltage of Node 1 in 1.5 seconds with different references

415400	414600	413800	413000	406200
412479	412583	412686	412790	407030

Table 3.1: Value of Voltage

The control action is shown in Figure 3.5. It starts into the admissibility region and follow the line of maximum and minimum power. This represent the saturation of the action control.

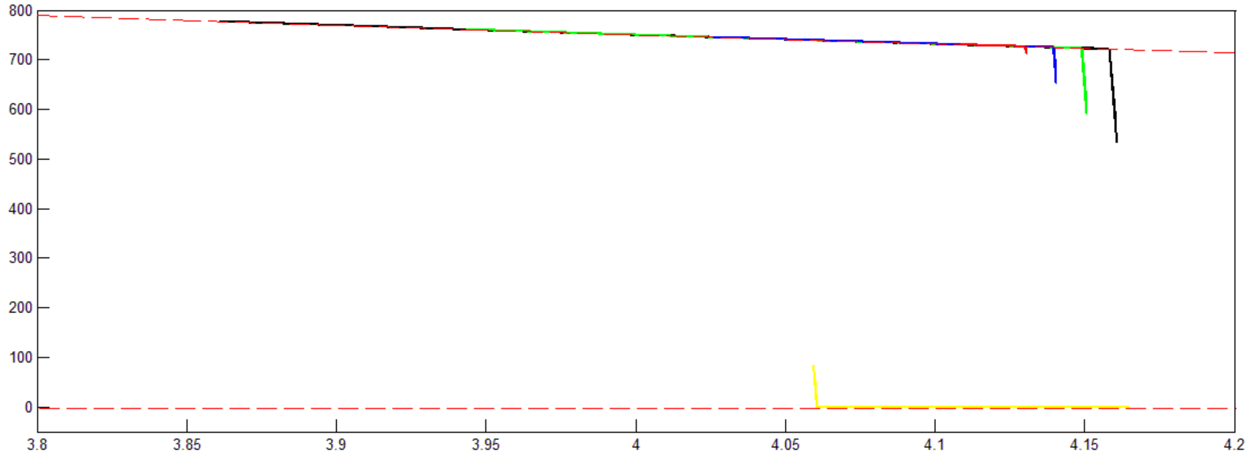


Figure 3.5: Action control of Node 1

In the Figure 3.6 and 3.7 there are the evolution of voltage and current of each nodes. the variations which depend on different voltage values are greater in the neighboring nodes. The Node n 2 has a change of voltage and current higher of other nodes because it is directly connect with Node n1. Farther is the node, lower is the change of voltage and current. For example, the Node n3 has a decimal variation of the voltage while Node n2 has a has a variation of two decimal orders. Node n4 and n8 have variation only in current.

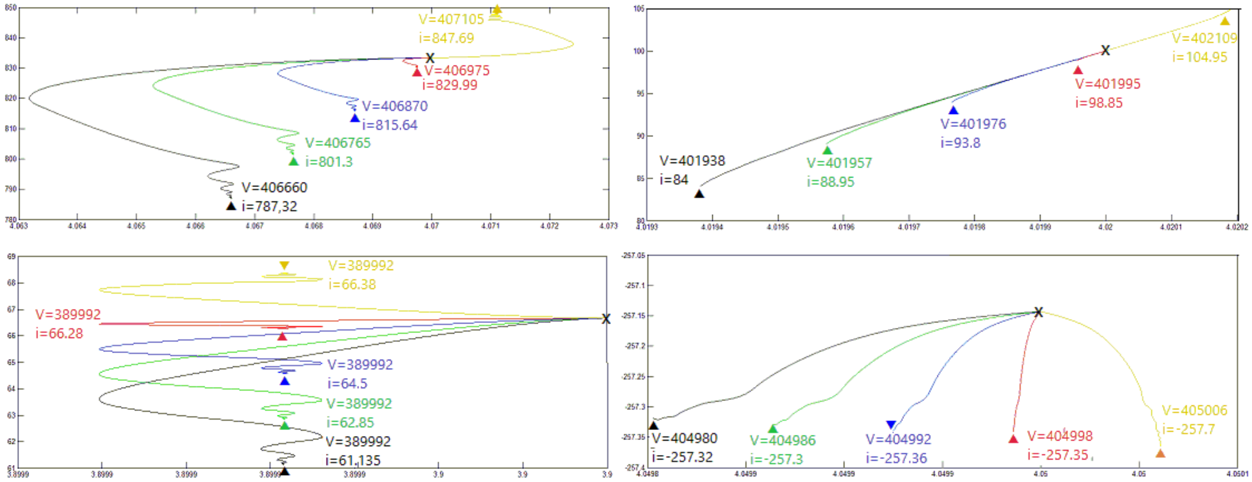


Figure 3.6: Evolution of state variables from Node 1 to Node 4

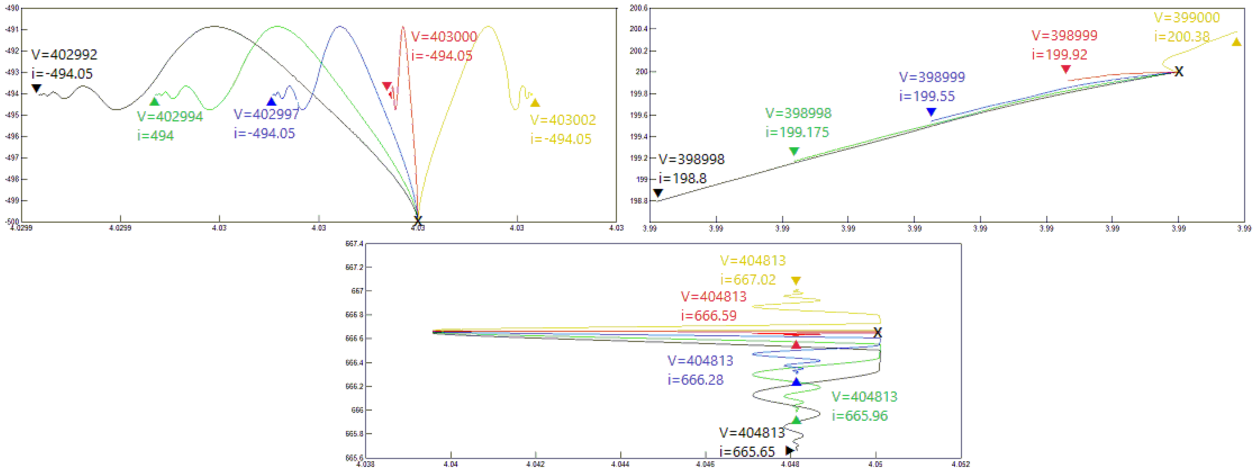


Figure 3.7: Evolution of state variables from Node 5 to Node 8

Figure 3.8 and Figure 3.9 show the trends of the voltages of each nodes in the first period. The simulation start from 0 second and finish to 0.5 seconds.

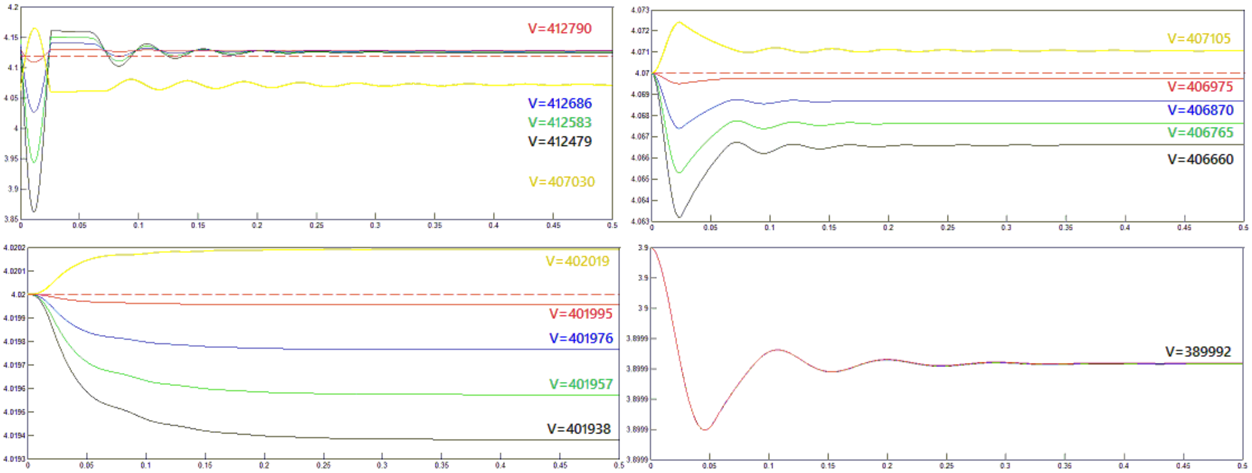


Figure 3.8: Voltages of first period: from Node 1 to Node 4

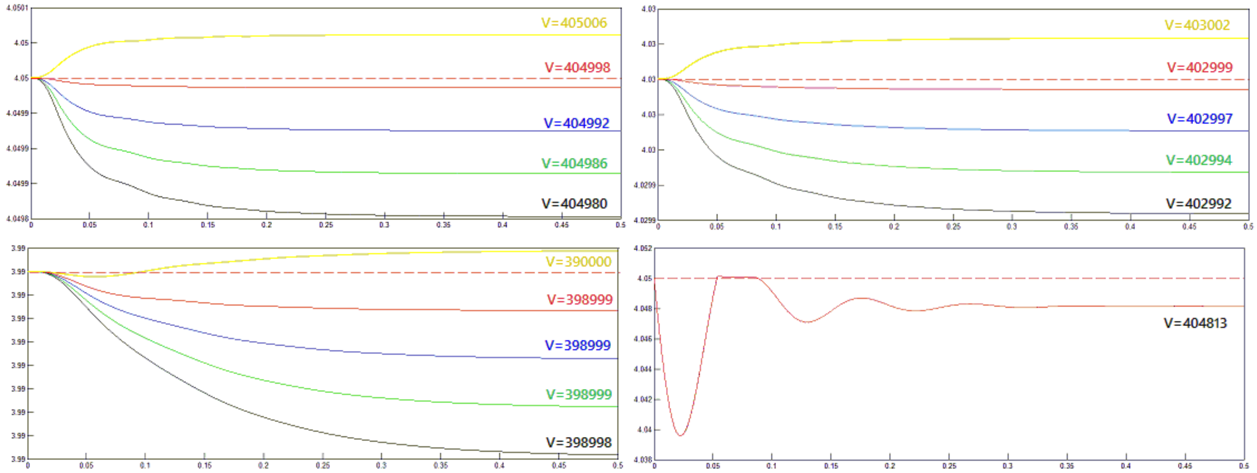


Figure 3.9: Voltages of first period: from Node 5 to Node 8

The variation of the first reference doesn't involve any change in the other periods. In this case, Node n1,n2 and n3, in the third period, have an oscillatory behavior. The other voltages follow the reference.

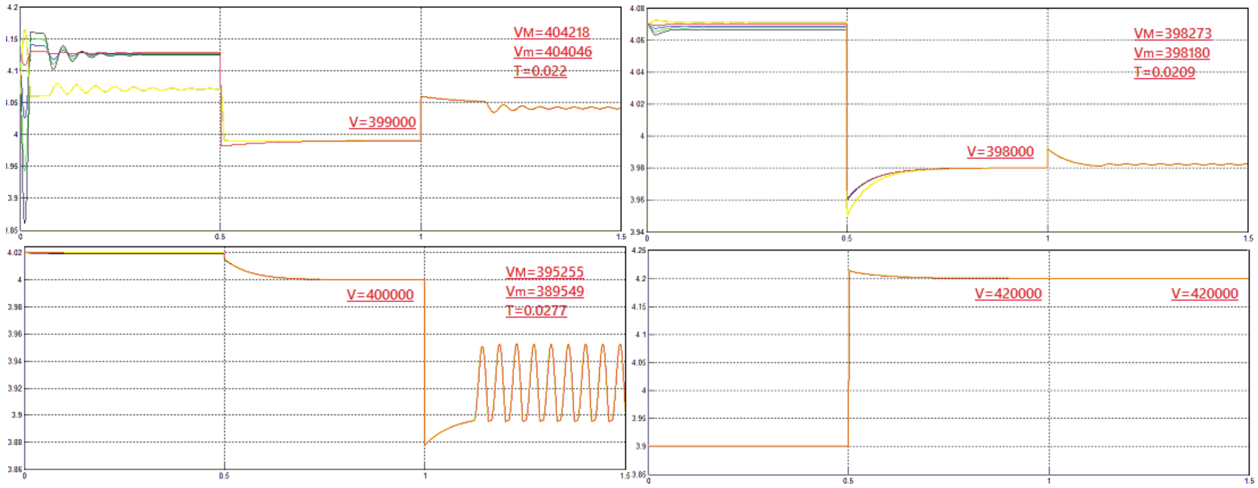


Figure 3.10: Voltages of all period: from Node 1 to Node 4

3.1.1.2 Node 8

This node is a node pour of connection. It has a direct connection only with Node n4. In the connected graph the current flow from the node n4 to node n8. The node n8 is far from the nodes with more connections like nodes n2 and n5. Consequently, when the node n8 changes the reference,other nodes suffer less influence than when changes take place in the node n1. For this reason, Nodes n1, n2 and n3 don't have some change. If the value of voltage lays between 390000 and 404000,the node stays in equilibrium, hence there are no significant variations in the state variables. That range of voltages represent equilibrium points for the system, because all nodes don't have some change in voltage and current.

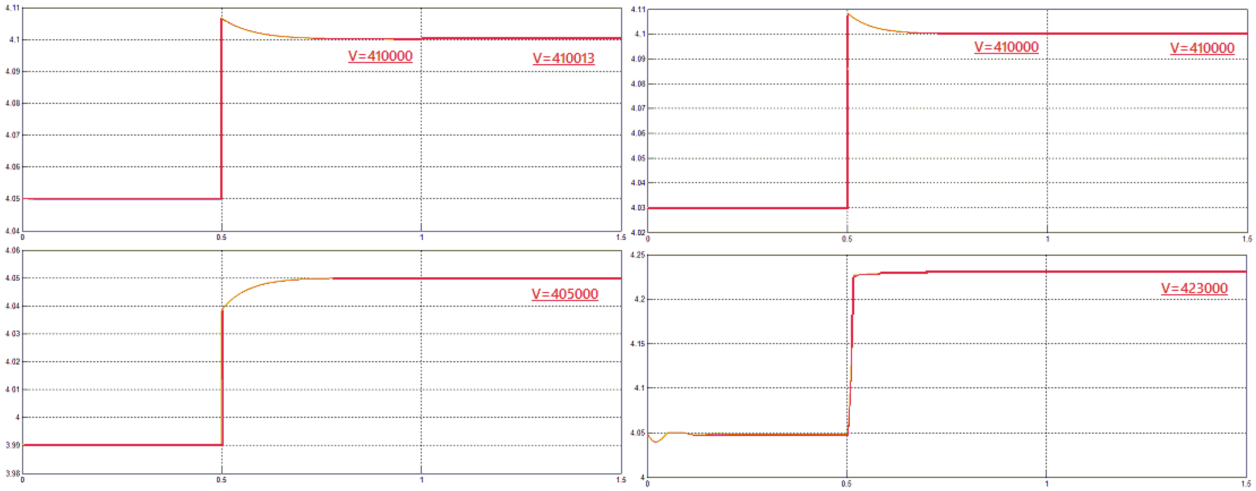


Figure 3.11: Voltages of all period: from Node 5 to Node 8

First are presented the changes in the node 8 when the reference in the same node are different. After, the thesis show the influence of that changes on the other nodes.

With a voltage greater than the value of 404000, the node n8 has an under elongation. Higher is the value of the reference, deeper is this under elongation and lower are the value of the voltage at 0.5 seconds. The transitory is slow if the value of the reference is high. The influence on the other nodes depend by the distance between the other nodes from node 8. Higher is the distance from Node n8, lower are the variations of Node n7, 6 and 5. This Nodes have respectively 1, 2 and 3 nodes of distance from Node 8. The changes in the far nodes n1, 2 and 3 are negligible. When the voltage of Node 8 has value equal to 413150 V, the node 7 has a pike in the transitory. Higher is the value of the voltage of node 8, higher is pike lower is the value of voltage at 0.5 seconds. The node 6 has the same behavior when the value of the voltage of node 8 is bigger than 413300 while the nodes 5, 1, 2 and 3 when the voltage is bigger than 413500.

When the value of the voltage of the node n8 is lower than 390000, the behavior is similar as the precedent case. In this case, in the transitory of voltage of the node 8 there isn't under elongation but upper elongation. Lower is the value of reference, higher is the value of voltage at 0.5 seconds. This behavior is the opposite of the other case.

When the initial condition are out of the admissibility region, the node stay out of this region,Figure 3.12. The system doesn't force the voltage and current of the node 8 to go into the admissibility region.

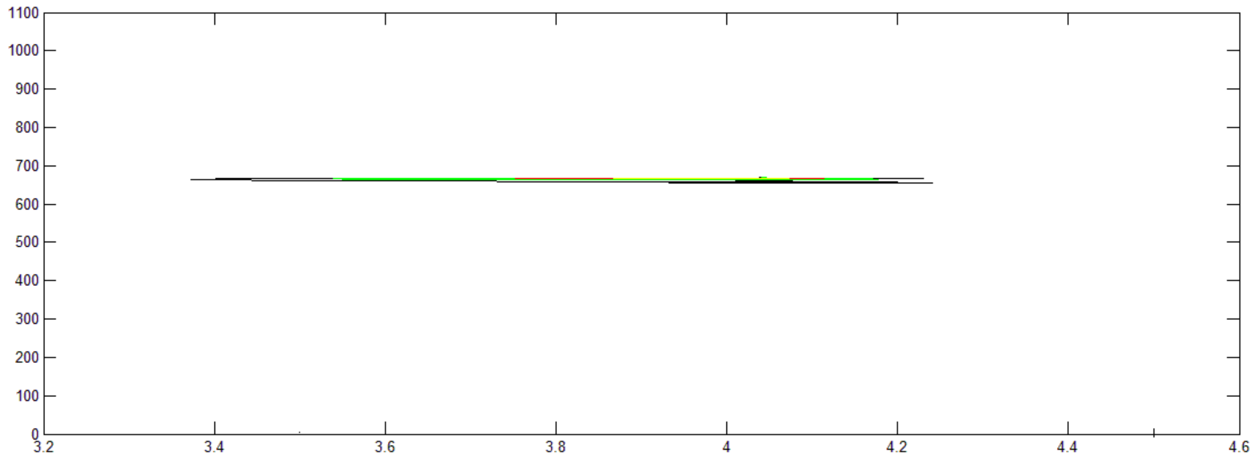


Figure 3.12: State space of Node 8

The Figure 3.13 show a zoom of the evolution of voltage and current of node 8. They start out of the admissibility region, and converge in different equilibrium point .

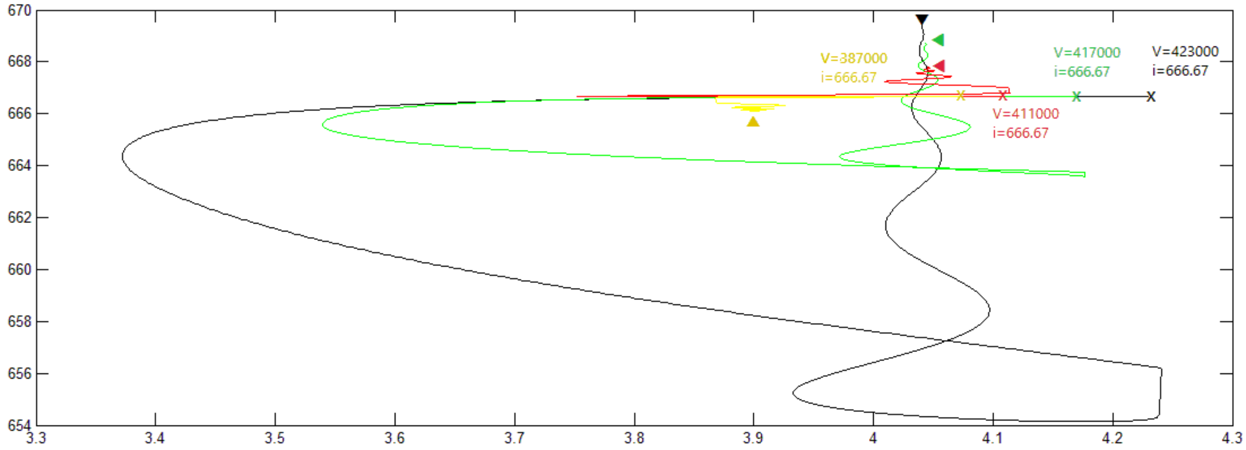


Figure 3.13: Zoom of evolution of Node 8

The under elongation, as possible to see in the Figure 3.14, is deeper in the black line who represents the bigger value of the reference.

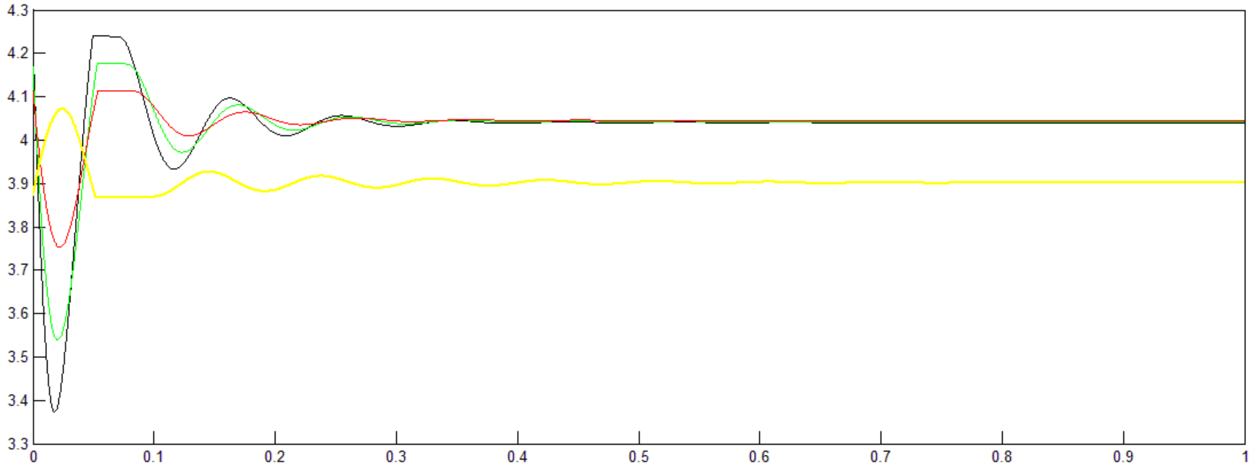


Figure 3.14: Voltages of Node 8 in the first period with different references

In the other period, there aren't change. It means that the changes in the first period don't influence the trend of the voltage in other period.

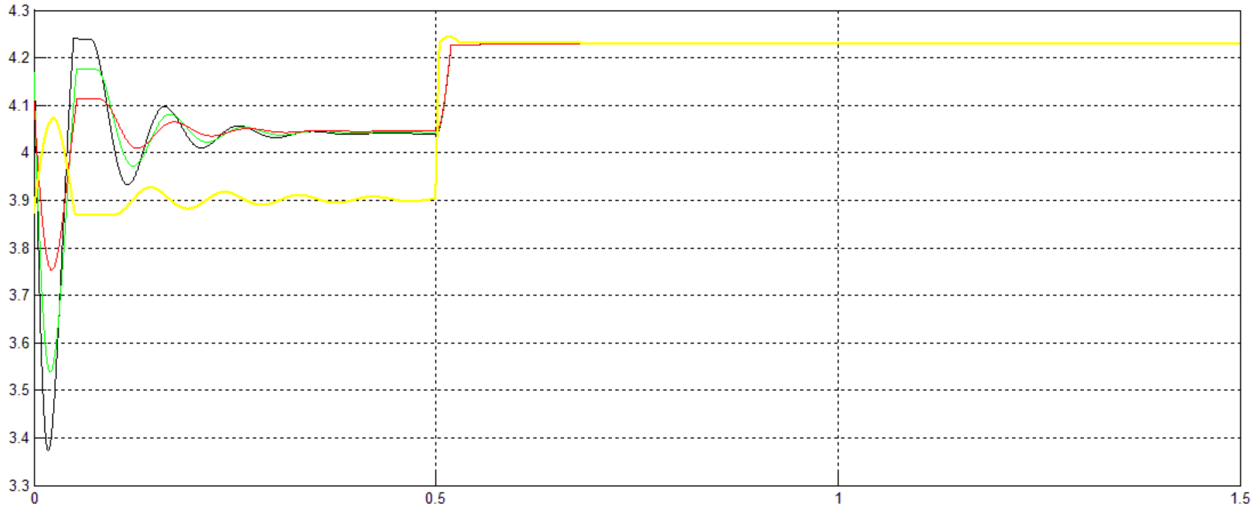


Figure 3.15: Voltages of Node 8 in the all periods with different references

The control action depends by the value of the reference. In Figure 3.16 as possible to see that the Node 8 start into the region and during the evolution, follow the red line who represent the maximum power of the node.

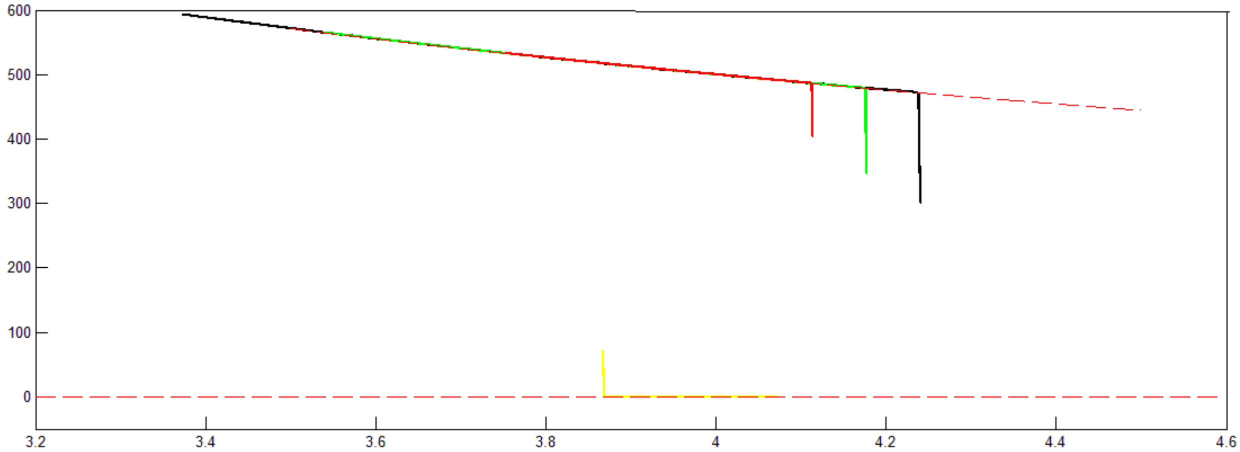


Figure 3.16: Control action of node 8

The Figure 3.17 and 3.18 show the evolution of state variables of all nodes when the references of the node 8 are different. The X represent the initial point and the triangle represent the equilibrium point where the state variable converge. The variation are signficative in the near node, like node 4 and 7. The far node, like node 1, 2 and 3 have little variation.

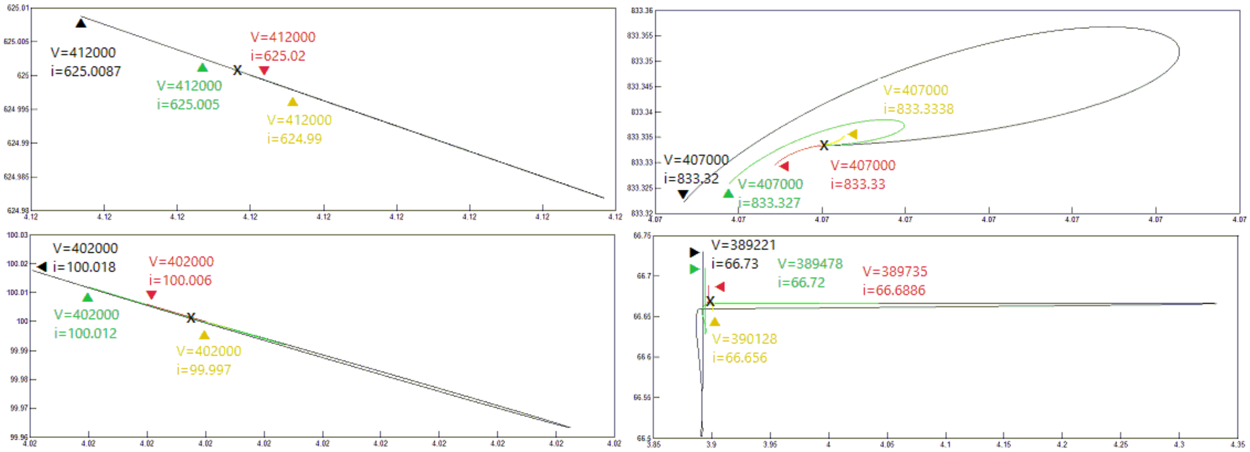


Figure 3.17: Evolution of state variables from Node 1 to Node 4

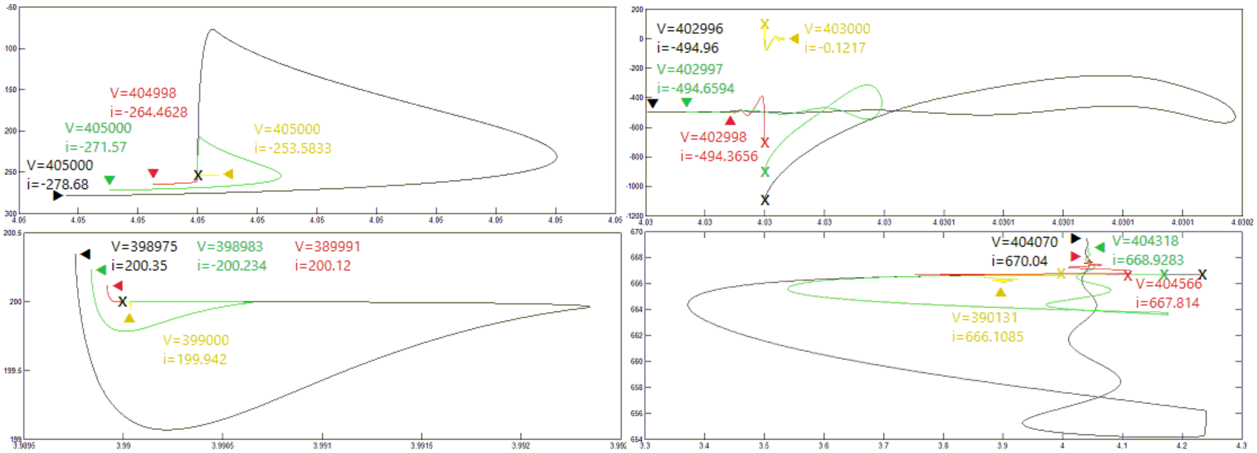


Figure 3.18: Evolution of state variables from Node 5 to Node 8

These Figure show the evolution of the voltage of each nodes in the first period. In this case, is possible to see the difference of the value of the voltages when the reference are different. The near node, like node 4, the value of voltage changes by 500 Volts. It depends by the different reference of the Node 8. A far node, like node 2, doesn't have some change in the voltage.

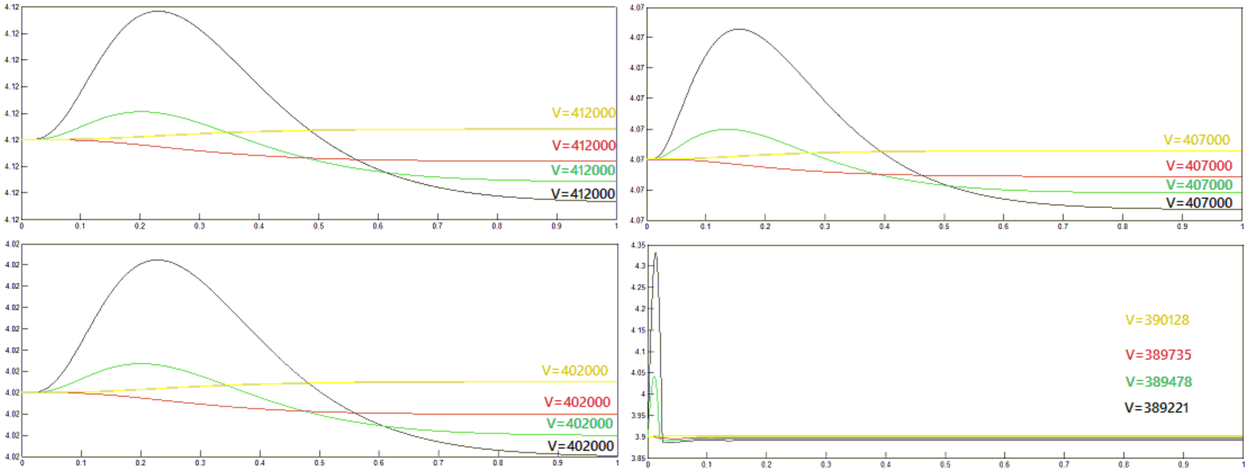


Figure 3.19: Evolution of Voltages in the first period: from Node 1 to Node 4

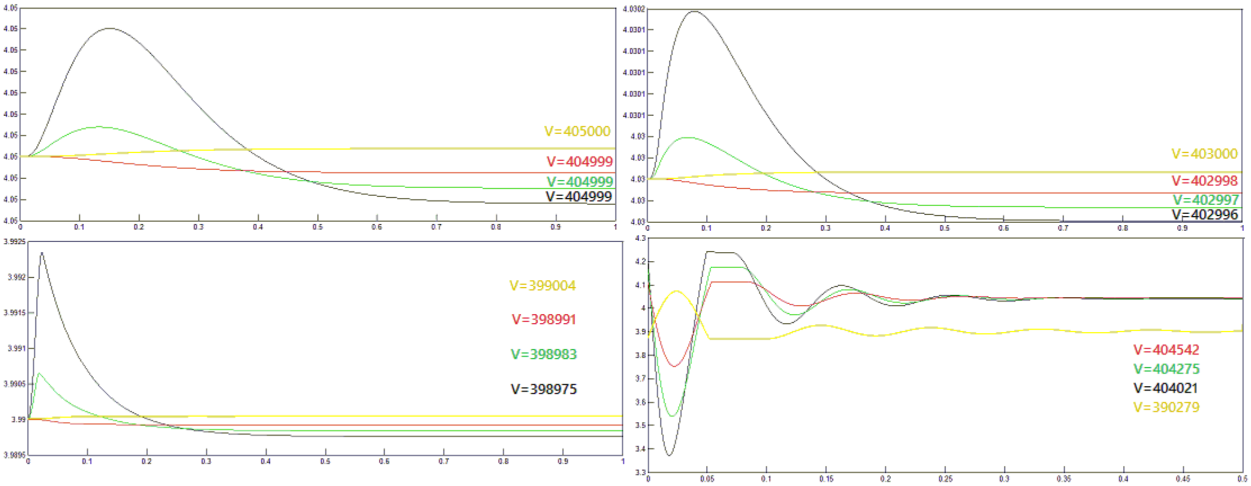


Figure 3.20: Evolution of Voltages in the first period: from Node 5 to Node 8

The voltages of node 1, 2 and 3 after 1 second present the oscillation also if the references of the first period are different. The other nodes converge to the references.

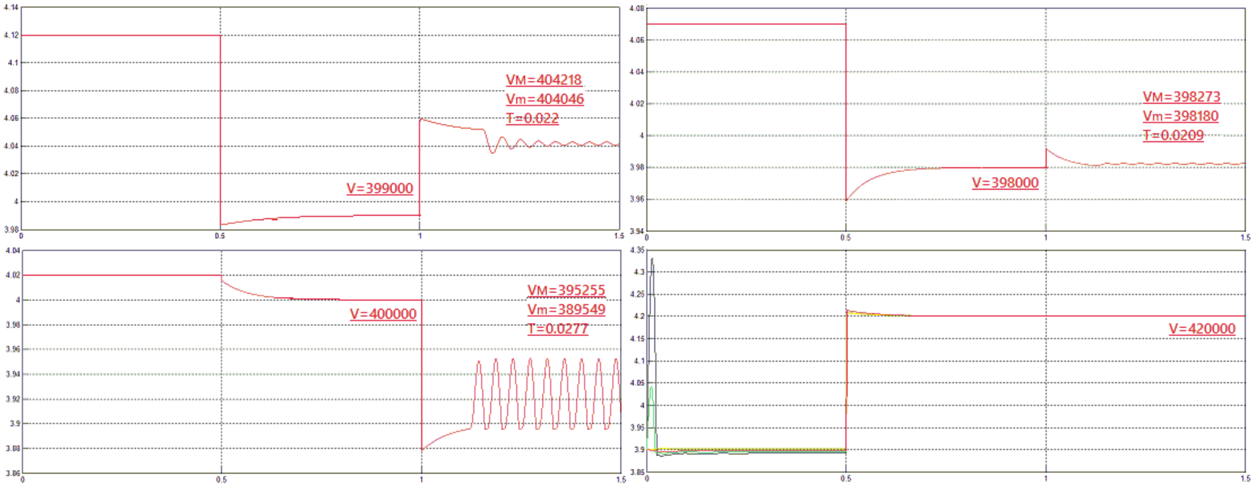


Figure 3.21: Evolution of Voltages in all periods: from Node 1 to Node 4

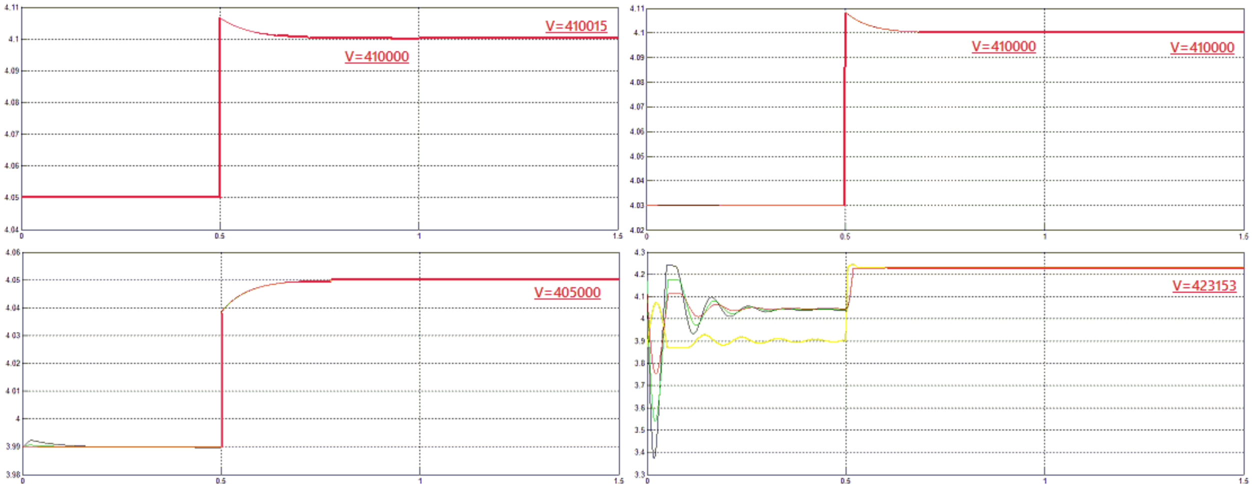


Figure 3.22: Evolution of Voltages in all periods: from Node 5 to Node 8

3.1.2 Hub

This kind of nodes have more connection with other nodes such as Node 2 who is connected with Node 3,5,6. This is the node who have the most number of connection of the network, but it's a little bit far from 2 nodes like Node 4 and Node 8.

3.1.2.1 Node 2

The node n2 is an Hub for the network. This involves, when there are some change in the reference of node 2 all node have a different level of variation: The near nodes have significant variation in the current and in the voltage; The far nodes have little variation. This variation are higher then the nodes pour of connection.The Node 2 is directly connect with node 1, 3, 5 and 6. The current in the connected graph flows from Node 2 to nodes 3, 5 and 6. With the variation of the reference in the first period, the trend of the state variables have different evolution. First, the thesis analyze the change on the node 2 and after the influence on the other nodes.

When the value of the reference is between 406200 and 407970, the voltage and current of node 2 don't have some variation. This range represent an equilibrium for all system because there aren't variation in all nodes. If the value of the reference is higher than 407970, the voltage of node 2 have oscillation. Higher is the reference, higher are the period and the amplitude of the oscillation of the voltage. In the transitory is present an under elongation. This under elongation is more accentuated if the value of the reference is more high. In facts, in Figure 3.29, the black line who represent the evolution of the voltage when the reference is equal to 414000, has the deepest under elongation. The variation of the reference in the first period doesn't involve variation of the voltage in the second and third period. The voltage has always an oscillatory trend. These are the reaction of the node 2. In the other nodes appear an oscillatory behavior. Only in the node 4 and 8 there isn't this behavior. Every node has a different amplitude and period that depend by the reference of the Node 2. Also in this case, the variation in the first period doesn't involve variation in the other period.

When the value of the reference is lower than 406200, there are different evolutions of the system. One type of evolution is when the value of the reference is higher than 402000 until 406200. In this case, Figure 3.35 and Figure 3.36, the voltage of node 2 has a little under elongation in the transitory and after 0.5 seconds the voltage is lower than the reference.

From 400130 Volt to 402000 Volt, the voltage of node 2 has an upper elongation in the transitory. Lower is the value of the reference, higher is the value of the pike of the upper elongation.

The voltage shown another kind of behavior when the reference has value bigger then 398770. In this case, the voltage of node 2 has a oscillation in the transitory. The oscillation vanish and the voltage converge to an equilibrium point that has a lower value of voltage than higher value of reference. Higher is the reference, lower is the pike of the upper elongation in the transitory.

Finally, with a value of reference lower than 398770, the voltage has a persistent oscillation. The period and the amplitude of the oscillation raise decreasing the reference.

The variation of reference of node 2 leads variation in other nodes. This changes are similar to those of node 2, but there are some exceptions: the node 3, 5 and 6 lost their oscillation when the reference of node 2 is bigger than 400000. In this case, the voltages of node show only an upper elongation.

The Figure 3.23 show the evolution of the state variables of node 2 when the reference are different. There are 2 different kind of references: the references with voltages higher than 406200 and the references with voltage lower than 398770. In Figure 3.23 there are both references.

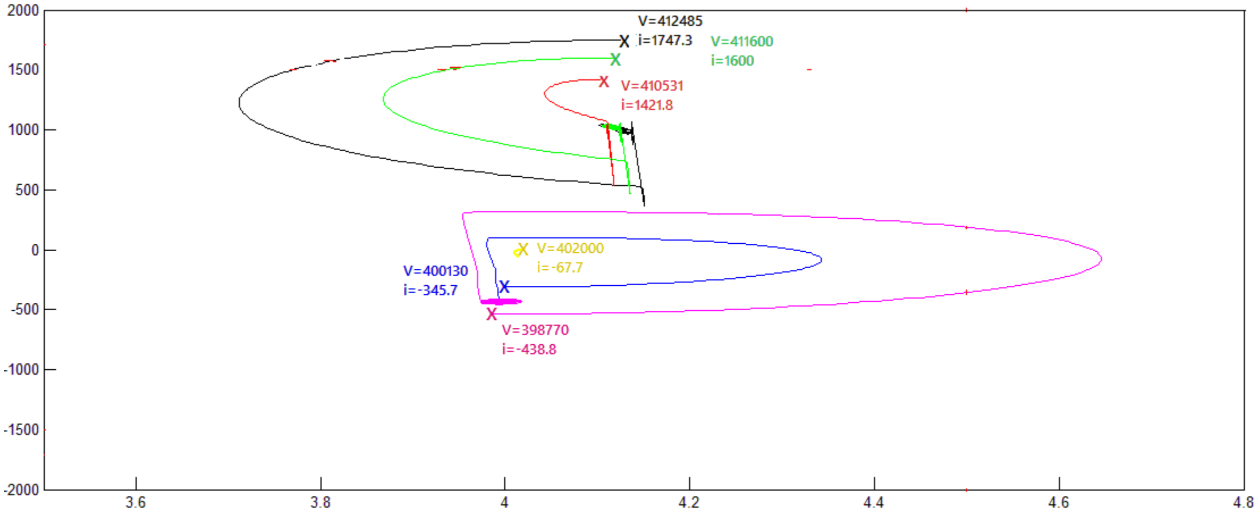


Figure 3.23: Evolution of state varaibles of Node 2

The evolution of voltage in the first period is shown in the Figure 3.24. In this case there are the evolution with all of references.

The change of references of the first period don't lead changes in the second and third period. The value of voltage is always the same, independent from the value of the reference.

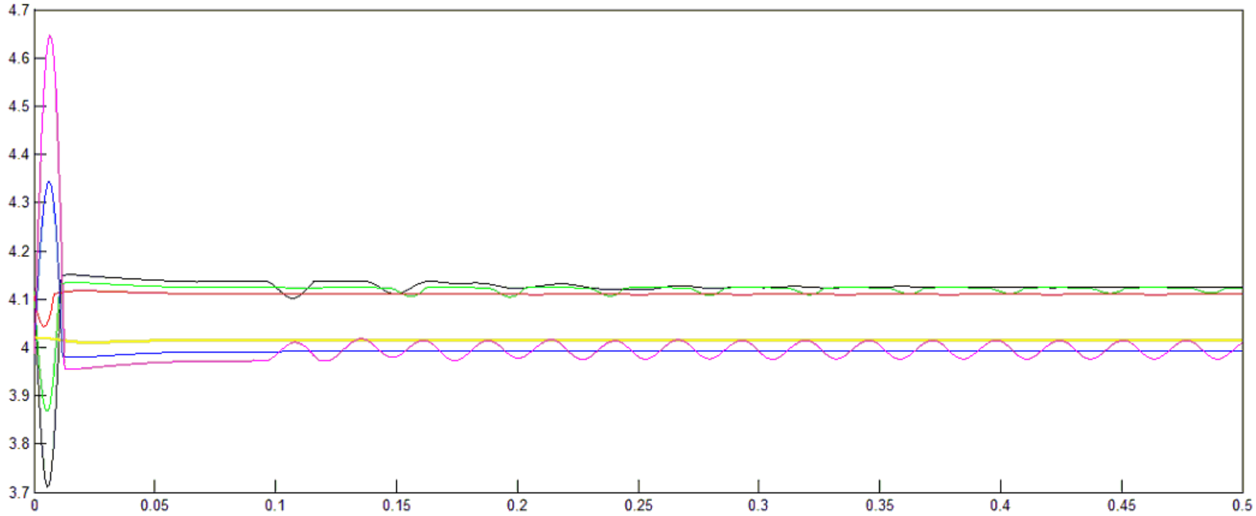


Figure 3.24:

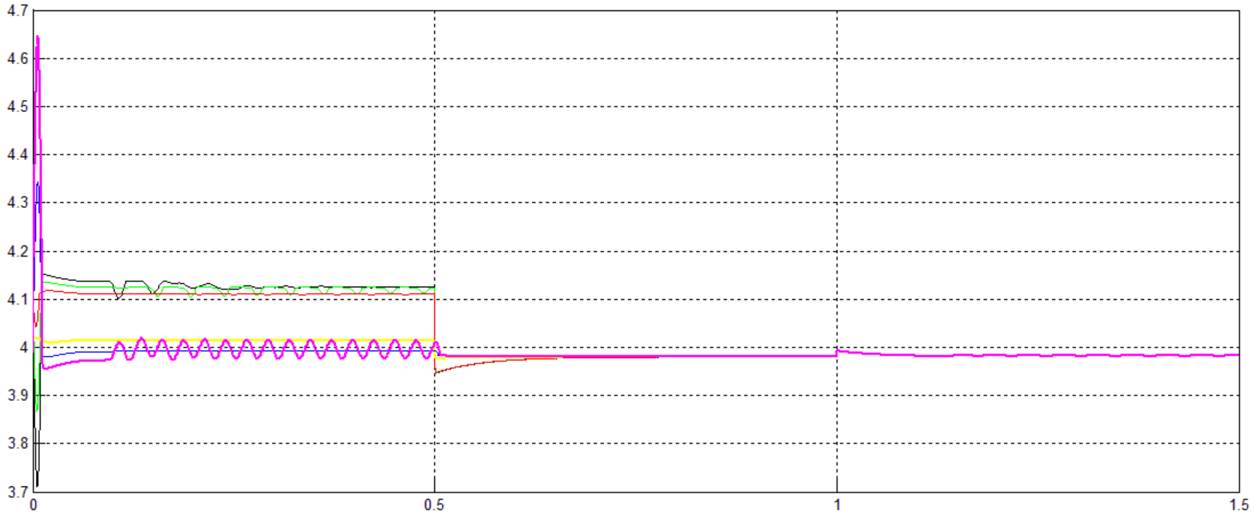


Figure 3.25: Voltage of Node 2

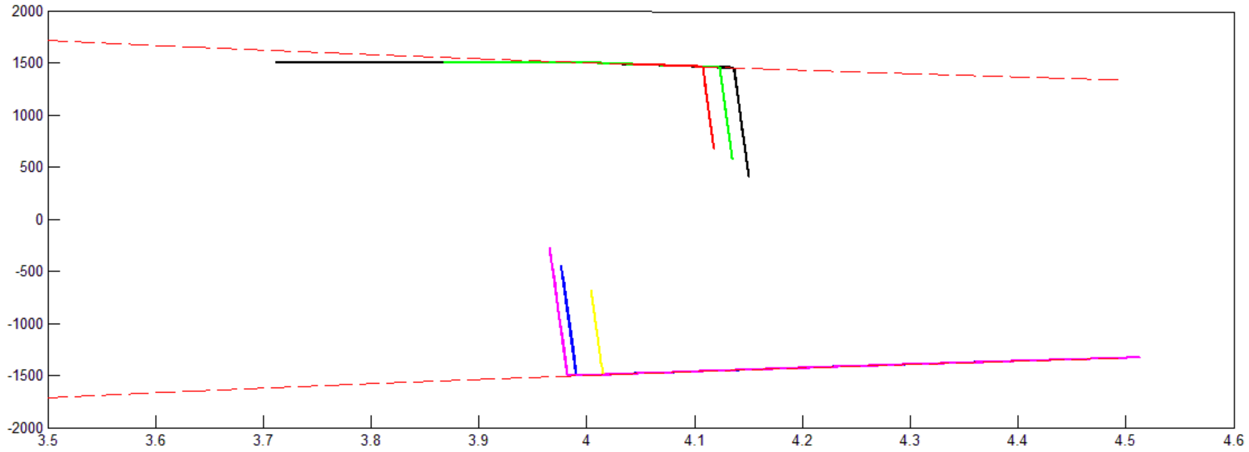


Figure 3.26: Control action of Node 2

The study of the evolution of the system and the influence of the change of the reference of node 2, is divided in two case. In Figure 3.27 and 3.28, there are the evolution of each nodes when the reference is higher than 406200. In the nodes 1, 2, 3 and 4 there are different initial point. The voltage is the same, but the current is different and depend by the references of node 2. In the other nodes, the initial point is always the same.

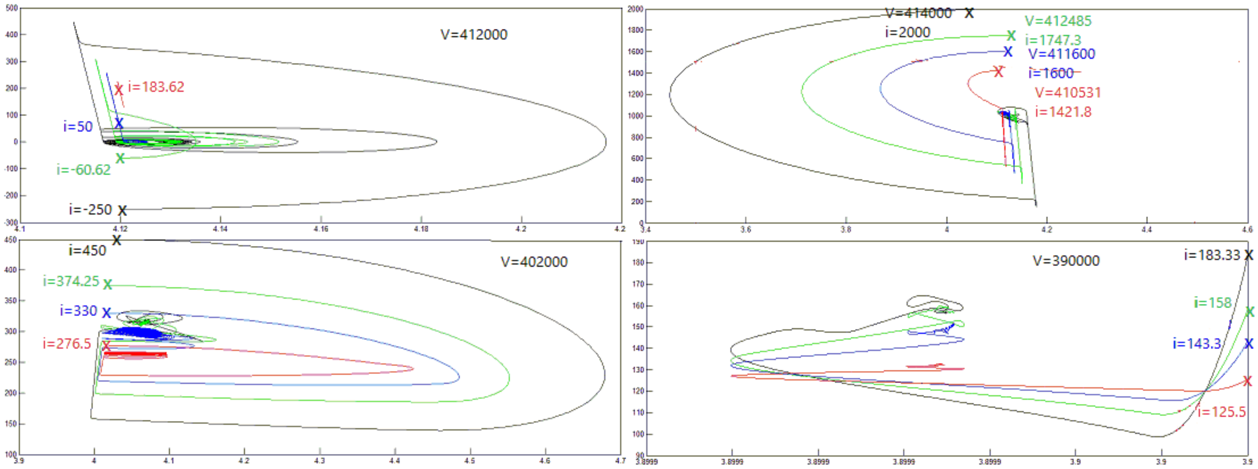


Figure 3.27: Evolution of state variables from Node 1 to Node 4

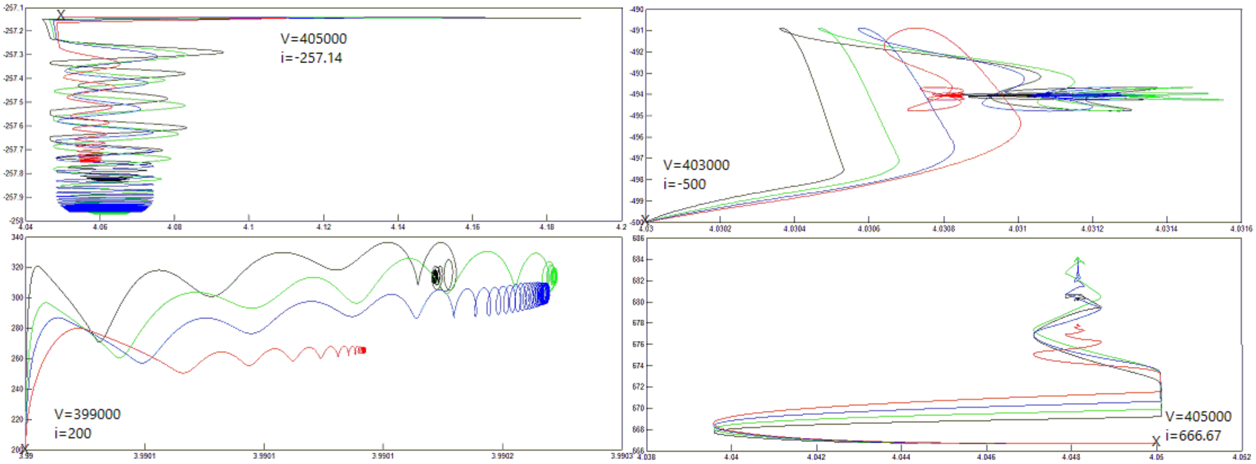


Figure 3.28: Evolution of state variables from Node 5 to Node 8

In every nodes are plot the maxim and minimum values and the period of the oscillation. There also the value of the pike of the under and upper elongation that depend by the different references.

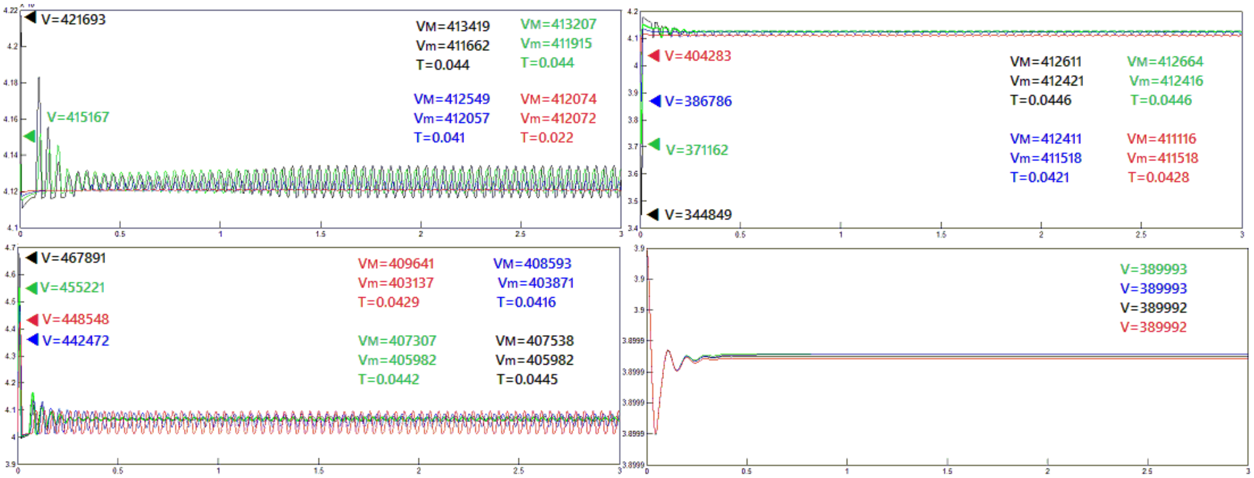


Figure 3.29: Evolution of Voltages in the first period: from Node 1 to Node 4

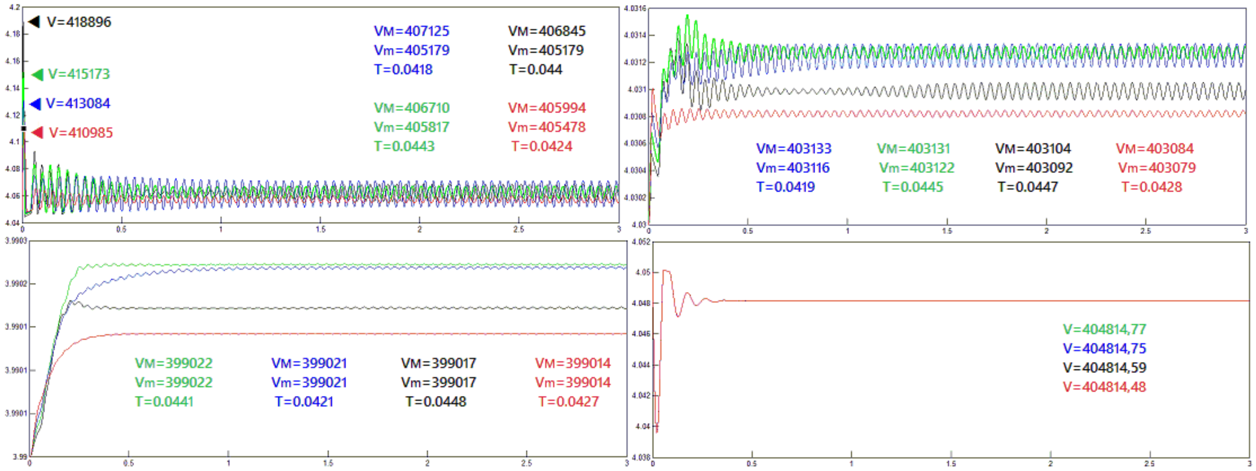


Figure 3.30: Evolution of Voltages in the first period: from Node 5 to Node 8

As usually, the changes of the references don't involve changes in the other period.

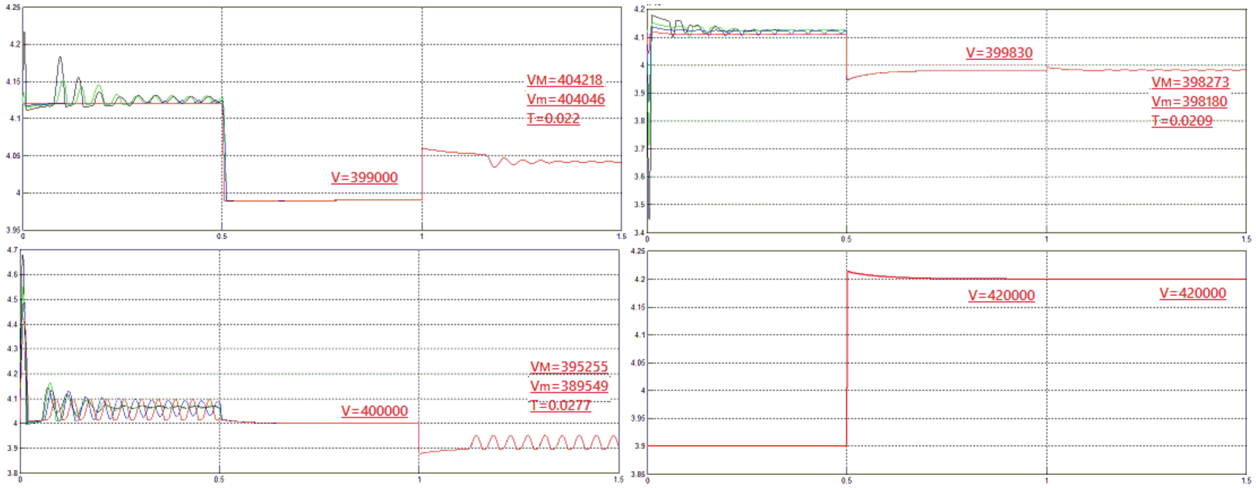


Figure 3.31: Evolution of Voltages in all periods: from Node 1 to Node 4

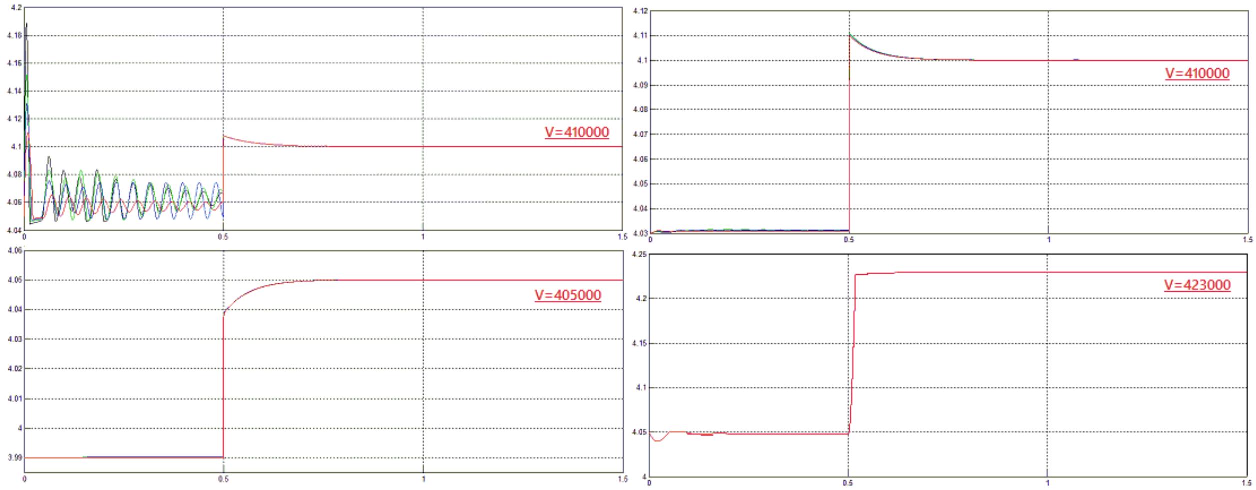


Figure 3.32: Evolution of Voltages in all periods: from Node 5 to Node 8

In Figure 3.33 and 3.34 there are the evolution of each nodes when the references of node 2 are lower than 406200. In this case there are different behavior who depends by the value of reference. Also here, nodes 1, 2, 3 and 4 have different initial current that depends by the value of reference. The voltages is always the same.

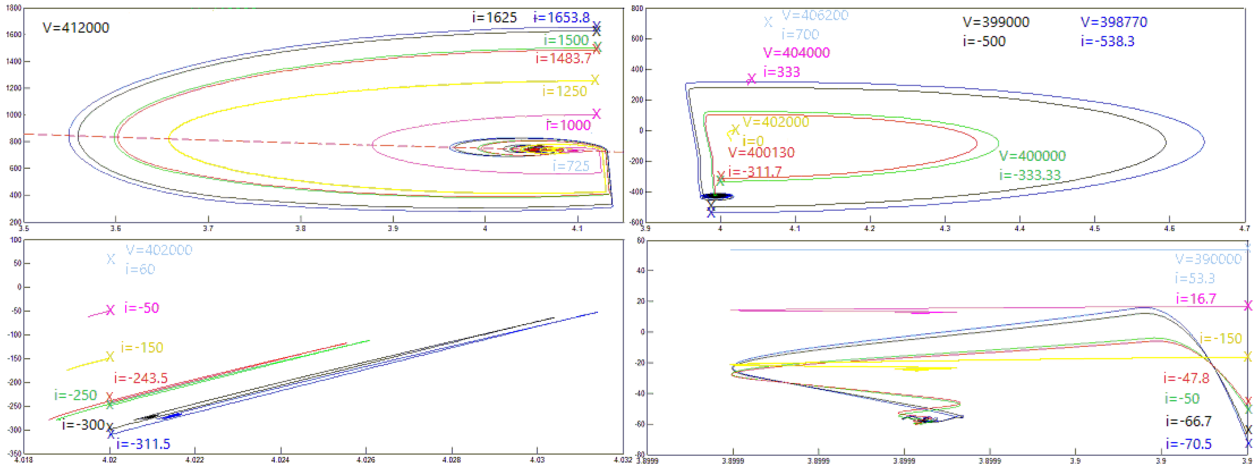


Figure 3.33: Evolution of state variables from Node 1 to Node 4

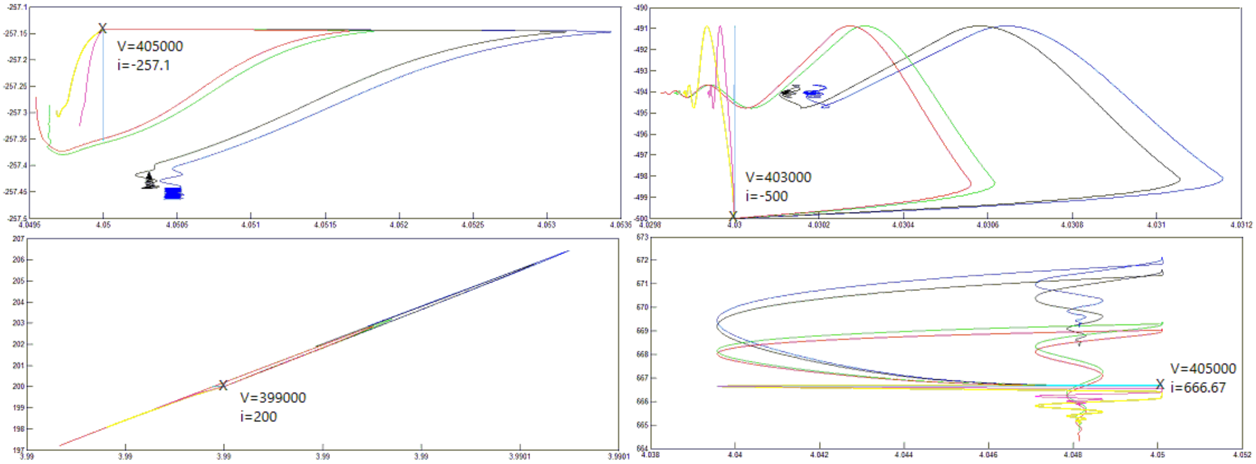


Figure 3.34: Evolution of state variables from Node 5 to Node 8

The influence of the variation of the reference of node 2 is very very strong in the node 1. The voltage of node 1 at 0.5 second is affected by the variation of the references. This influence become less effective for the 3, 5 and 6.

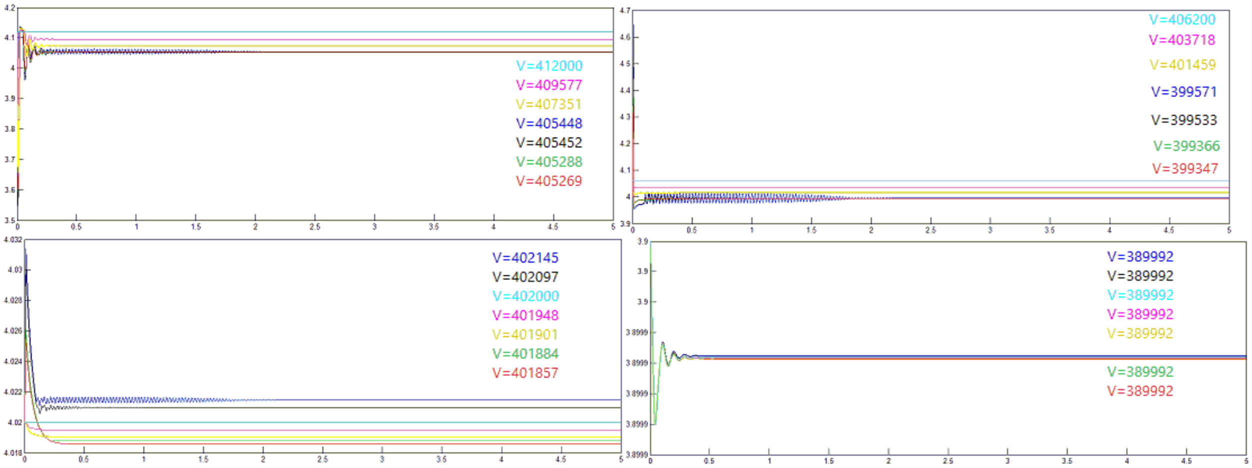


Figure 3.35: Evolution of Voltages in the first period: from Node 1 to Node 4

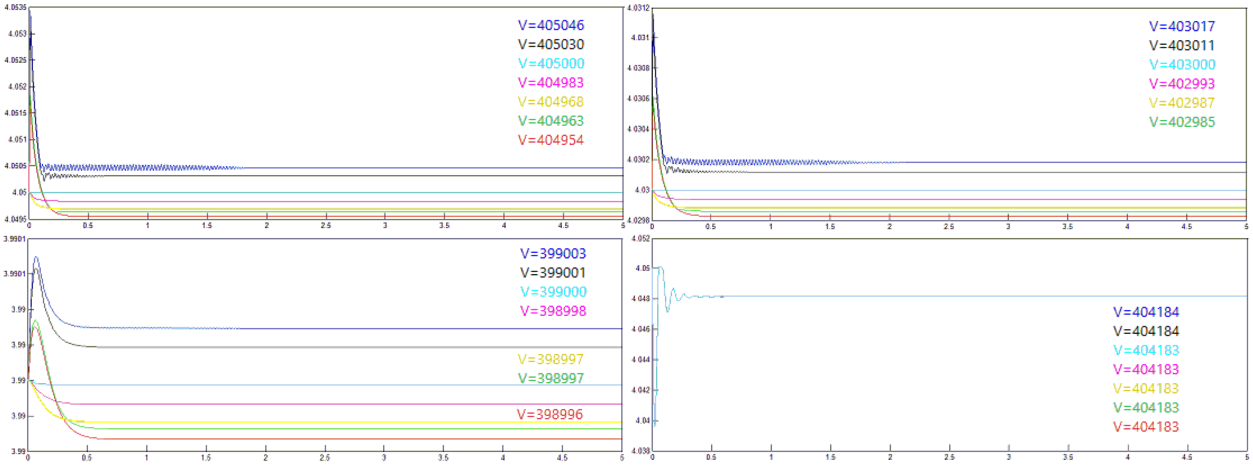


Figure 3.36: Evolution of Voltages in the first period: from Node 5 to Node 8

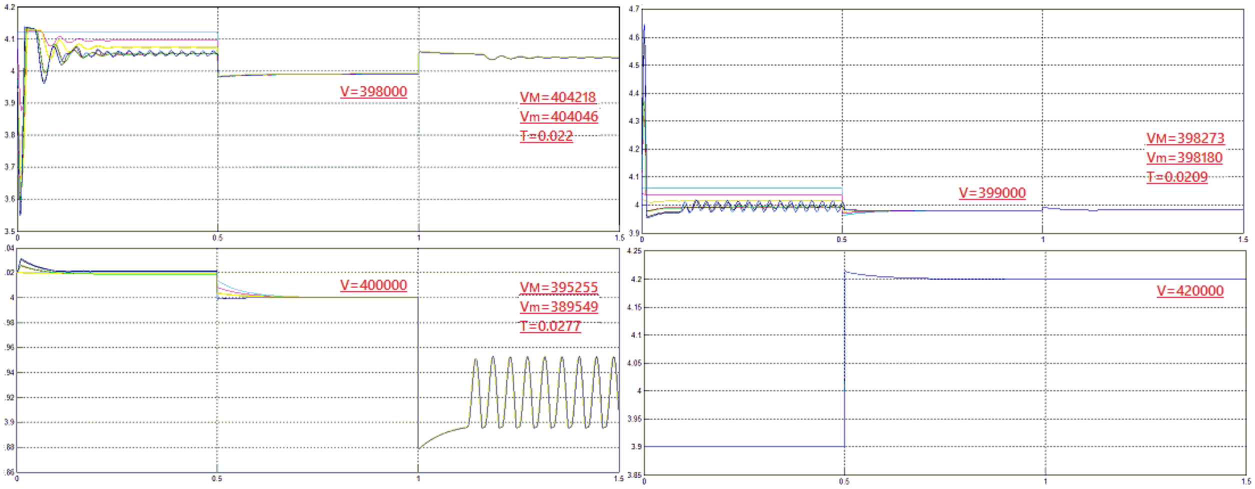


Figure 3.37: Evolution of Voltages in all periods: from Node 1 to Node 4

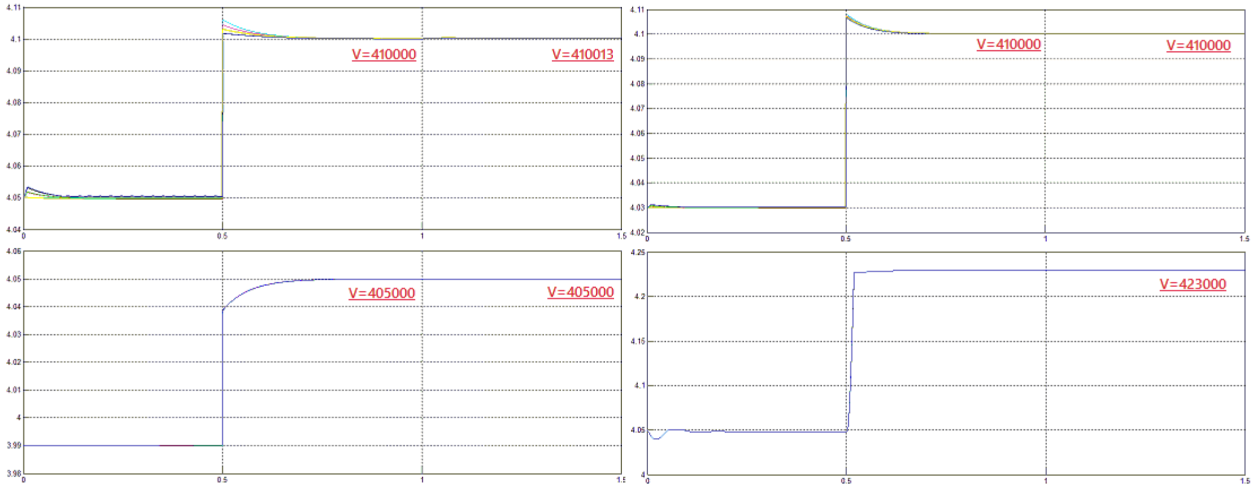


Figure 3.38: Evolution of Voltages in all periods: from Node 5 to Node 8

3.2 Lower value of the proportional gain

This section analyze the system when the value of the proportional control is variable. Different value of the proportional control leads a different reaction of the system to the variation of the reference. In a graph where the x-axis represent the voltage and y-axis represent the control current, different value of the proportional control represent different relation between voltage and current. Lower is the inclination of the straight line of control, lower is the saturation because the system stays in the admissibility region for a long time. The choice of the value of the control action is based on the behavior of the nodes. Lower is the value of the action control, higher are the amplitude and the period of the oscillation after 1 second. The oscillatory trends is present in the nodes 1, 2 and 3. For values of control action lower than 0.041, the nodes 1, 2 and 3 lost they oscillatory behavior. In facts, they converge to a different value. Lower is the value of control action, lower is the values that converge the nodes.

3.2.0.1 Node 1

This section studies the difference between 2 different control action when the values of the references of node 1 are out of the admissibility region. Figure 3.39 shows the evolution of state variables when the references are out of the admissibility region and the value of proportional control decrease. The dashed lines represent the evolution of state variables when the value of the proportional control is equal to 0.041. The full line represent the evolution with the value of control action is equal to 0.0189. In this way, for any reference there are 2 evolution. With the same reference, lower is the value of the control, lower is the value of the voltage at 0.5 second. During the evolution of the system, with the action control equal to 0.041, the voltage assume higher values than the voltage with action control equal to 0.0189. The influence for the variation of the references on the other nodes is more high when the value of the control action is low.

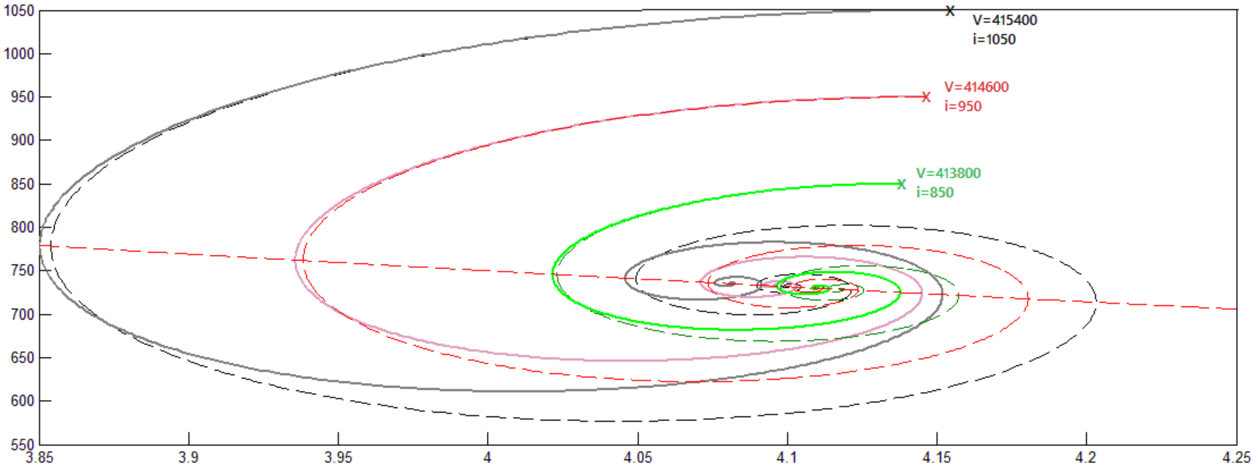


Figure 3.39: Evolution of state variables of Node 1 with action control equal to 0.041 (dashed lines) and equal to 0.0189 (full lines)

The Figure 3.40 is a zoom of the equilibrium points. This points are on the line who represent the maximum power for the node.

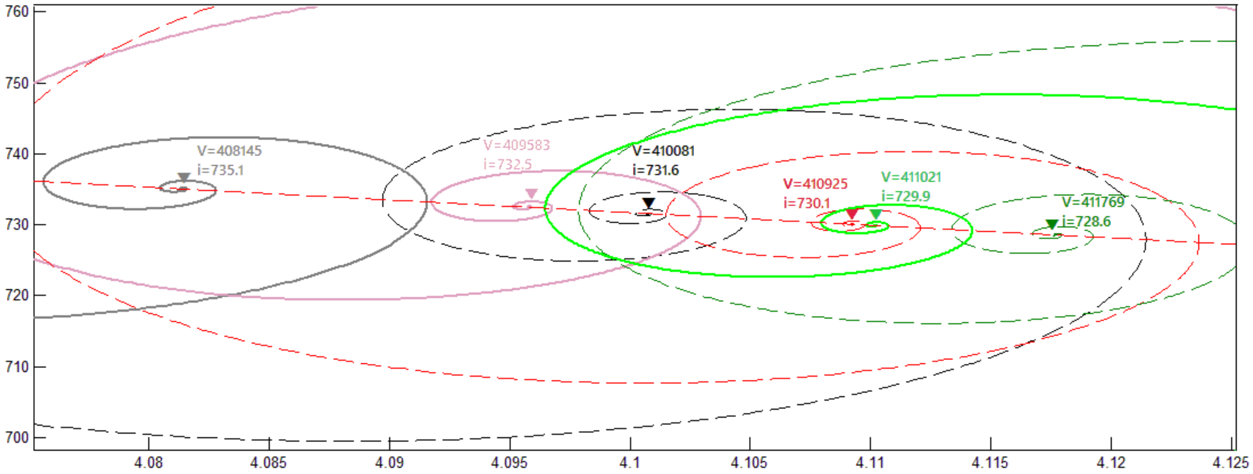


Figure 3.40: Equilibrium point of Node 1

The Figure 3.41 and 3.42 show the evolution of each nodes when the reference of the node 1 in the first period changes. Lower is the value of proportional control, higher is the influence on the other nodes. In facts, Nodes 4 and 8 are affected by the change of the reference.

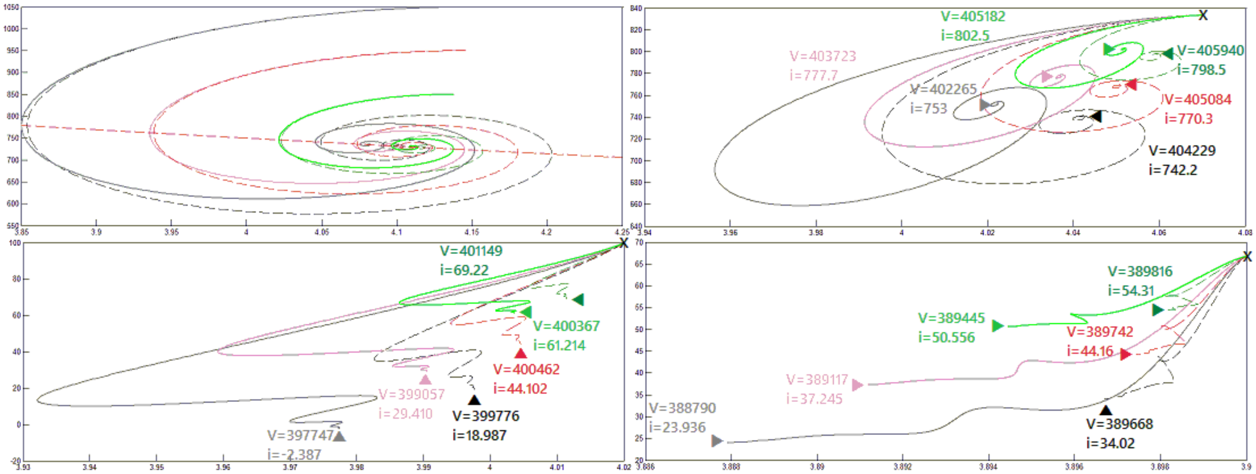


Figure 3.41: Evolution of state variables in the first period with different references and value of control action equal to 0.041 (dashed lines) and equal to 0.0189 (full lines): from Node 1 to Node 4

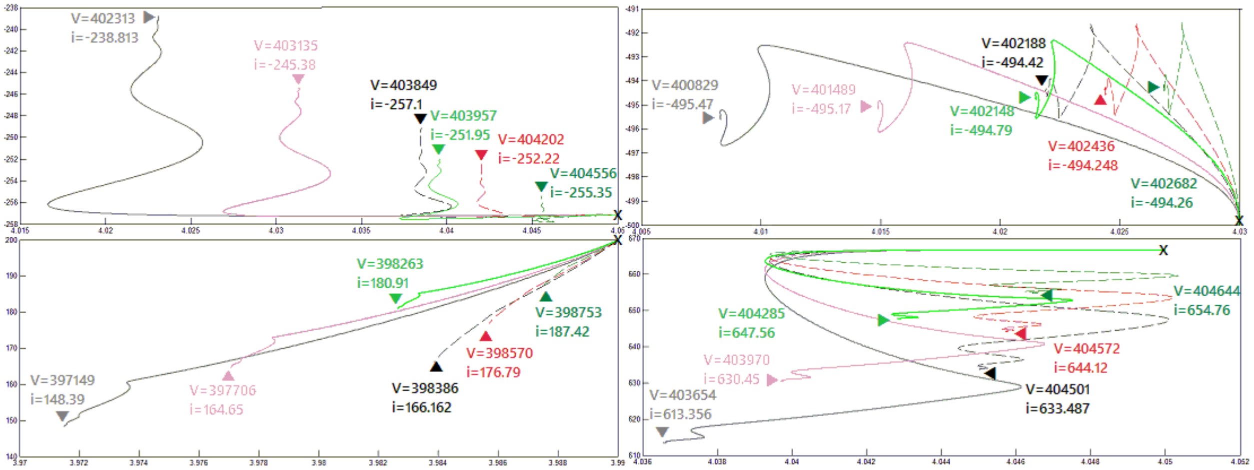


Figure 3.42: Evolution of state variables in the first period with different references and value of control action equal to 0.041 (dashed lines) and equal to 0.0189 (full lines): from Node 5 to Node 8

The values of the voltages depend by the control action. The full lines are lower then dashed lines.

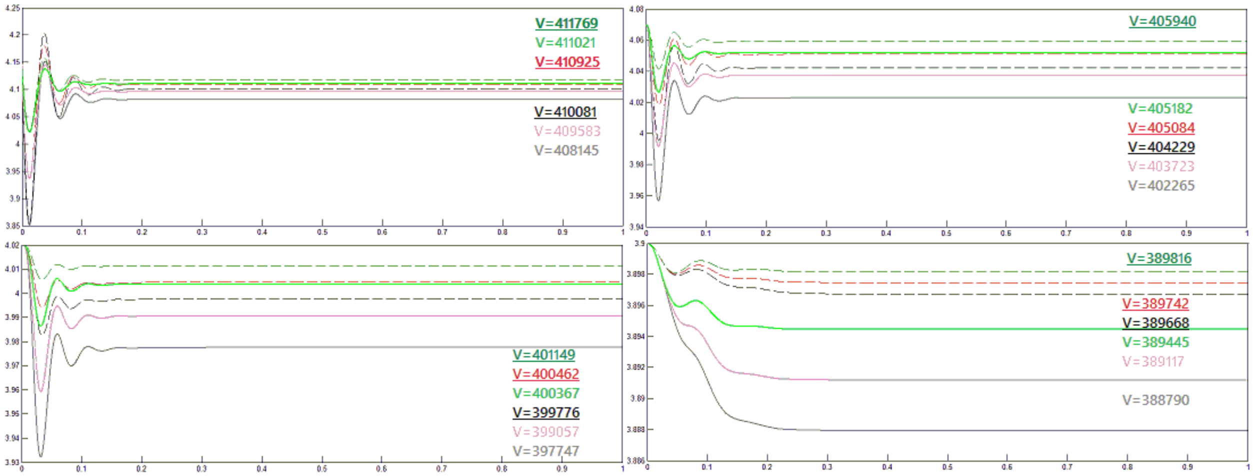


Figure 3.43: Evolution of Voltages in the first period with different references and value of control action equal to 0.041 (dashed lines) and equal to 0.0189 (full lines): from Node 1 to Node 4

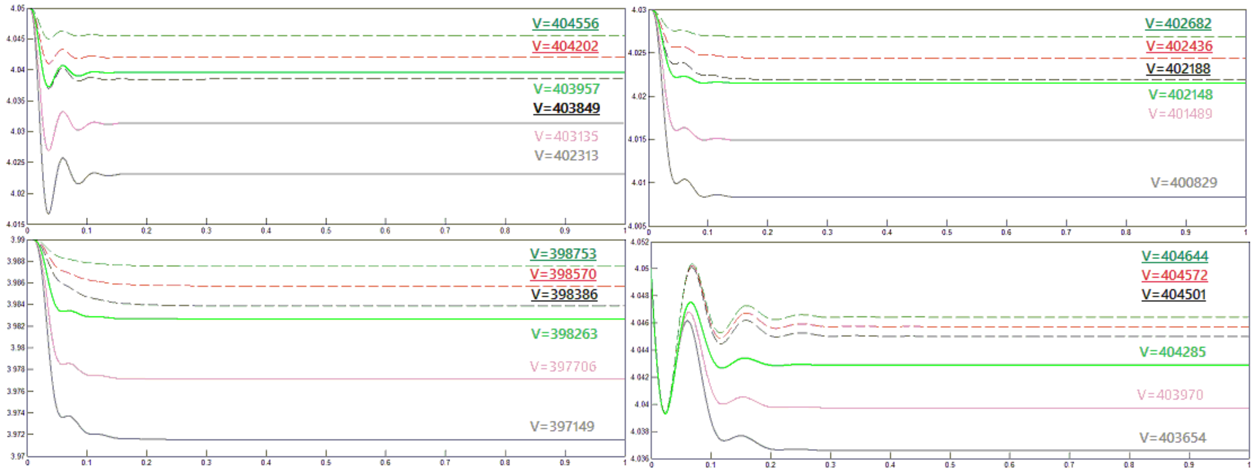


Figure 3.44: Evolution of Voltages in the first period with different references and value of control action equal to 0.041 (dashed lines) and equal to 0.0189 (full lines): from Node 5 to Node 8

The Figure 3.45 and 3.46 show the trends of the voltages of all nodes. In this case, they value of the proportional control is equal to 0.041. Node 1, 2, 3, 5 and 6 have an oscillatory behavior in the last period. It depends by the control action. The values of the references for the first period, are the same of the case with the value of proportional control equal to 0.75. Higher is the reference, lower is the value of voltage at 0.5 seconds. In the transitory of the second and third period appear under elongation and upper elongation. The far nodes, like node 4 and node 8, don't have variation.

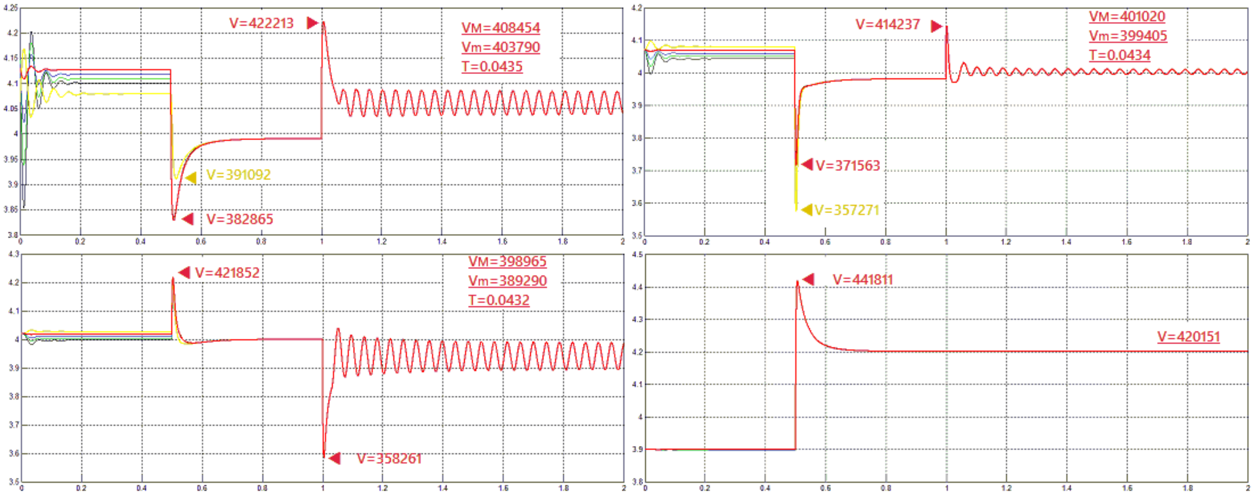


Figure 3.45: Evolution of Voltages in all periods with different references and value of control action equal to 0.041: from Node 1 to Node 4

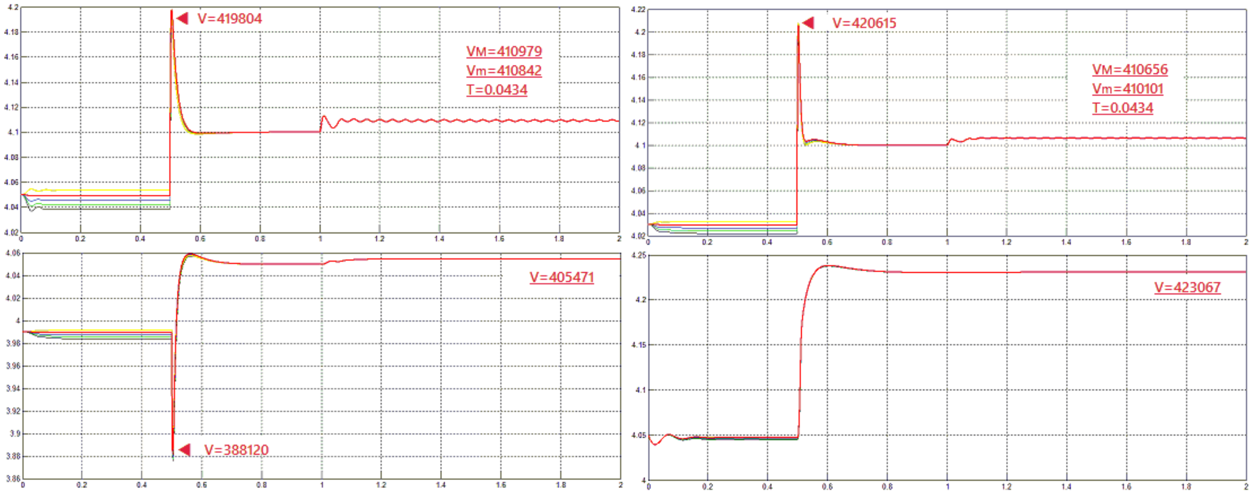


Figure 3.46: Evolution of Voltages in all periods with different references and value of control action equal to 0.041: from Node 5 to Node 8

In the Figure 3.47 and 3.48 the control action is equal to 0.0189. The oscillatory trend disappears in all nodes, but the pike of the transitory of the second and third assume higher values than the pike in Figure 3.45 and 3.46. In the nodes 3 and 4 the voltages go out the admissibility region, because the voltages assume respectively lower and higher values of voltage than the minimum and maximum limit of the admissibility voltages. All of the other nodes are affected by the change of the references on node 1. Also far nodes present some variation. Particularly the value of the voltages after 1.5 seconds are different from the reference of the nodes.

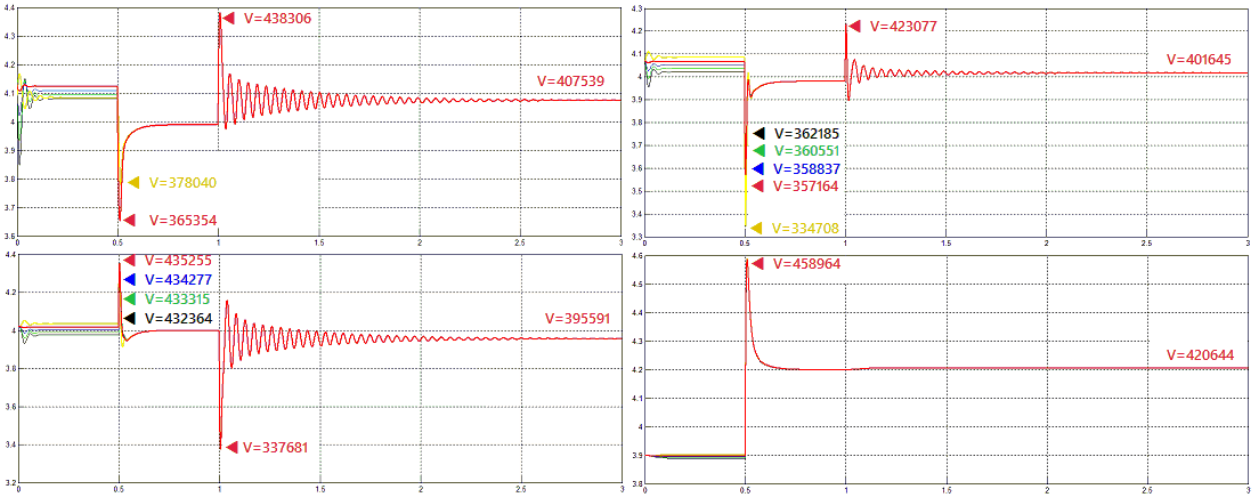


Figure 3.47: Evolution of Voltages in all periods with different references and value of control action equal to 0.0189: from Node 1 to Node 4

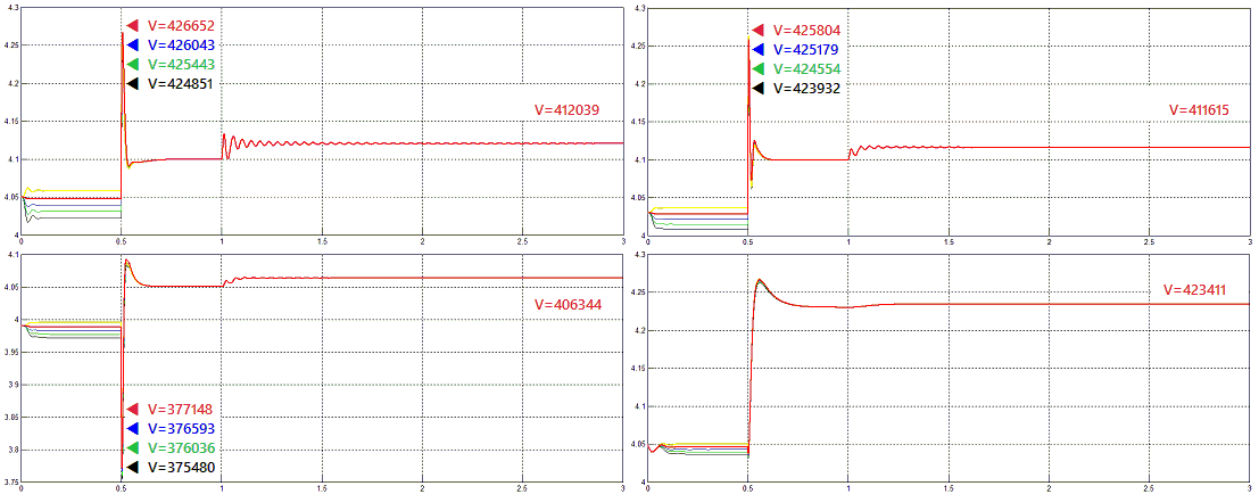


Figure 3.48: Evolution of Voltages in all periods with different references and value of control action equal to 0.0189: from Node 5 to Node 8

3.2.0.2 Node 8

In Figure 3.49 there are the evolution of the state variables when the reference of the node and the control action are variable. The Node starts out of the admissibility region. Lower is the the of the control action, lower are the values of the voltage at 0.5 seconds. The start points have different value of voltages but same values of current.

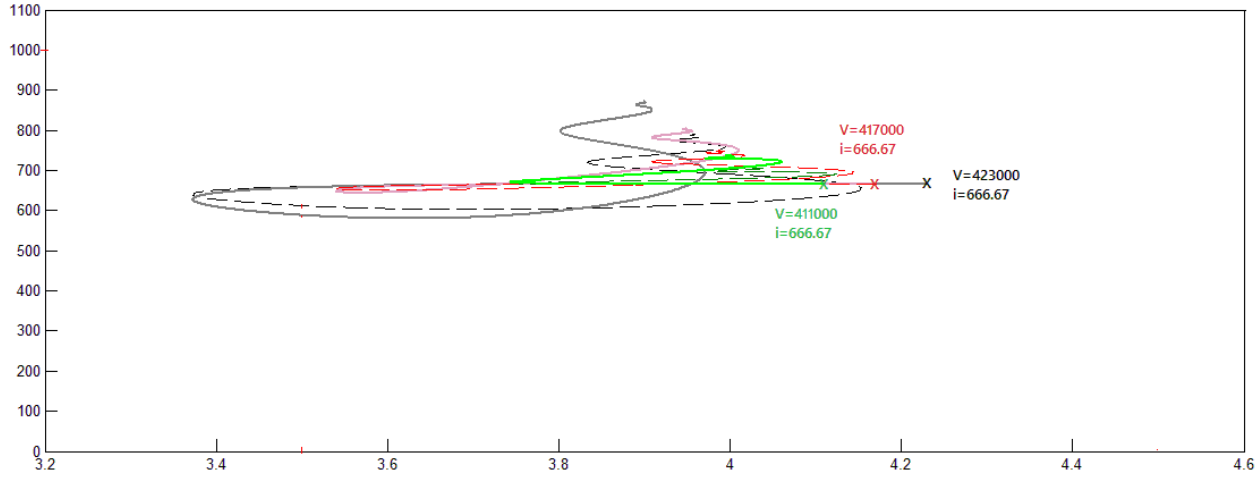


Figure 3.49: Evolution of state variables Node 8 with action control equal to 0.041 (dashed lines) and equal to 0.0189 (full lines)

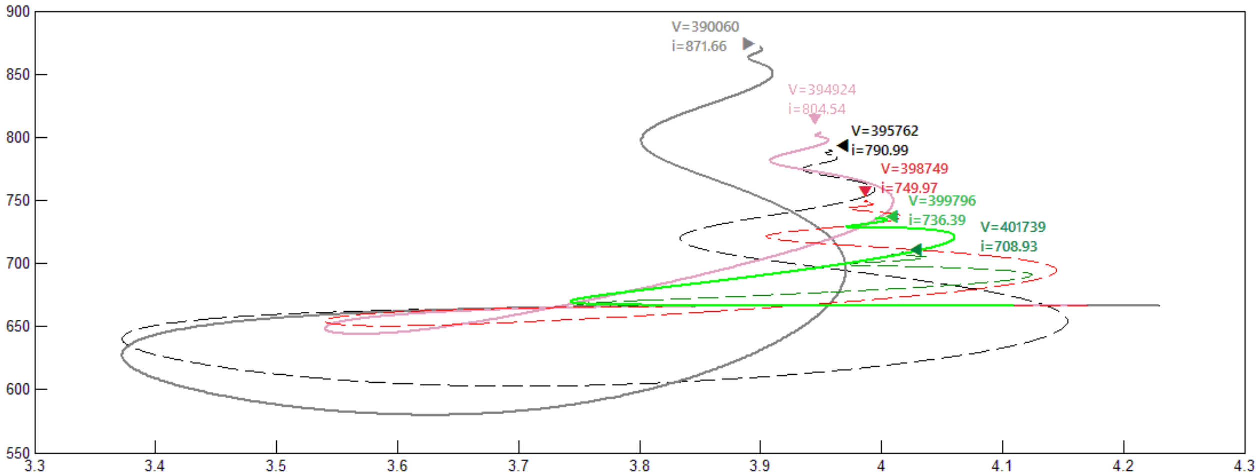


Figure 3.50: Equilibrium point of Node 8

The evolution of all nodes are plot in Figure 3.51 and Figure 3.52. When the reference of node 8 is change all nodes are affected. Also the far node, like nodes 1,2 and 3 present variation in the state variables.Also for this node, lower is the value of the proportional control, lower is the value of the voltage of each nodes at 0.5 seconds. When the reference of node 8 change, the start points of nodes 6 and 8 are different.

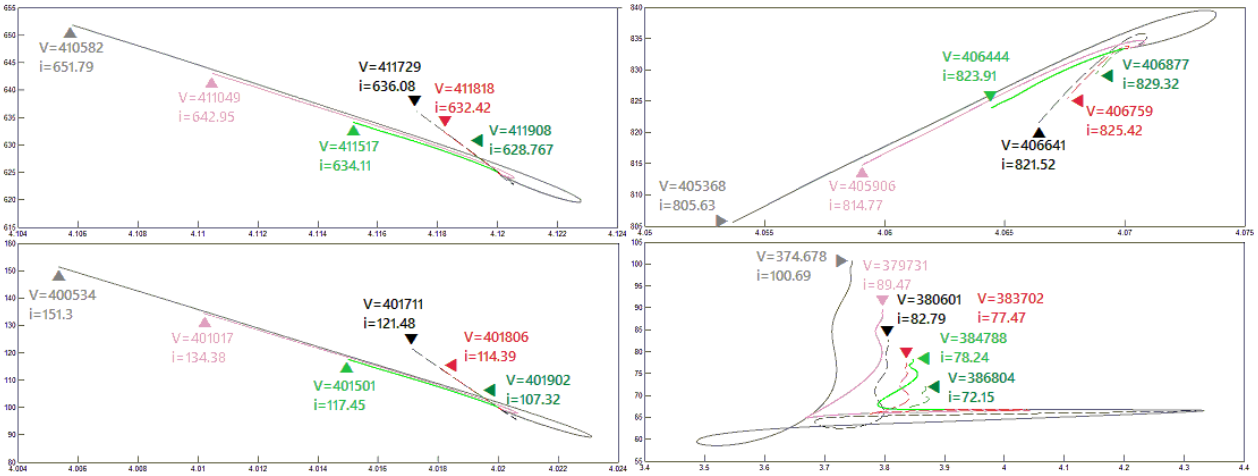


Figure 3.51: Evolution of state variables in the first period with different references and value of control action equal to 0.041 (dashed lines) and equal to 0.0189 (full lines): from Node 1 to Node 4

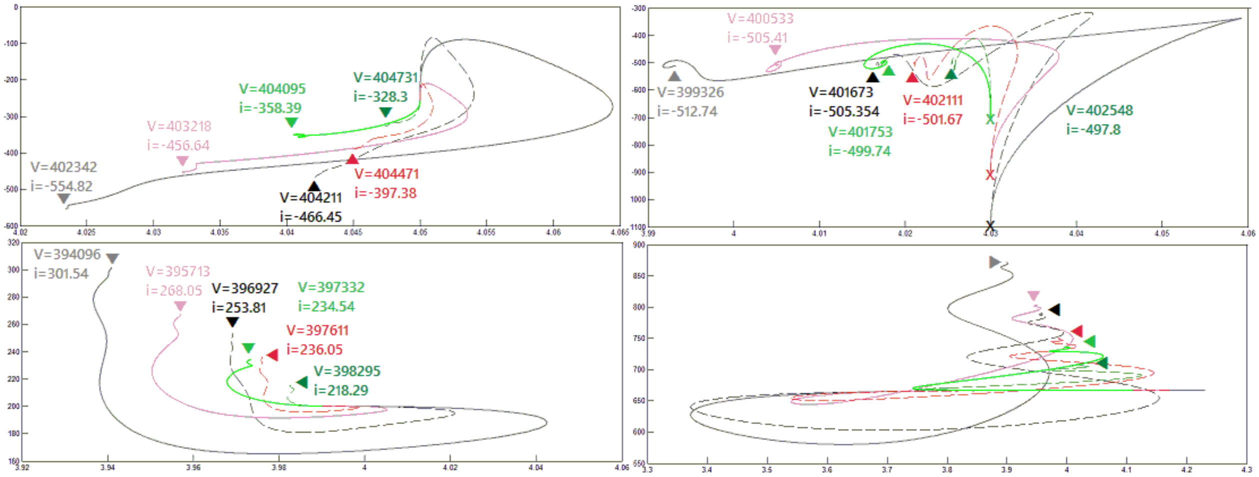


Figure 3.52: Evolution of state variables in the first period with different references and value of control action equal to 0.041 (dashed lines) and equal to 0.0189 (full lines): from Node 5 to Node 8

Farther are the nodes from node 8, lower are the variation. Furthermore, lower are the value of the control action, higher are the influence in all nodes. As usually the dashed line represent the control action with the value of control equal to 0.041 and the full line the control equal to 0.0189.

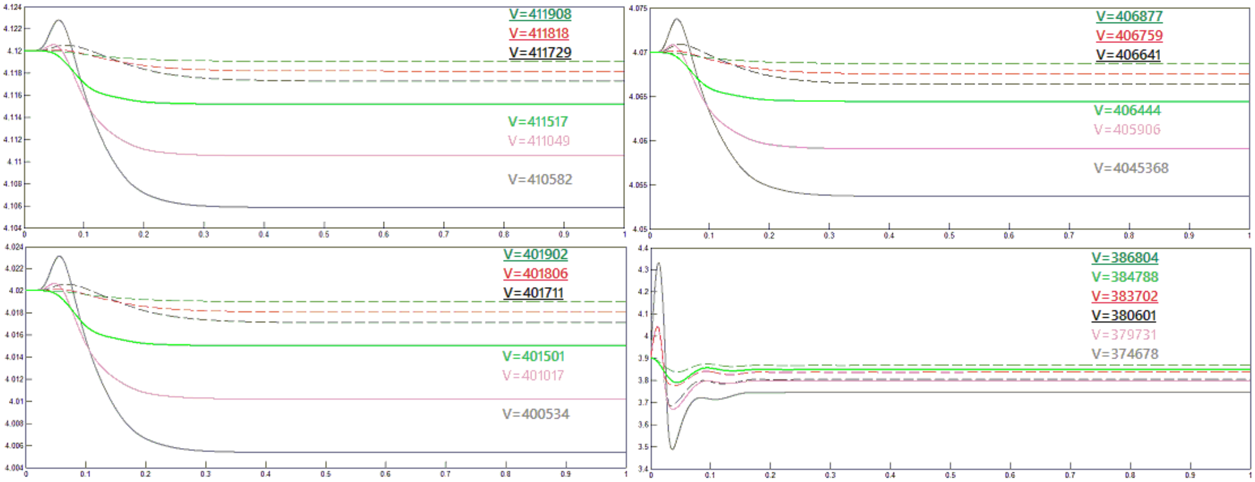


Figure 3.53: Evolution of Voltages in the first period with different references and value of control action equal to 0.041 (dashed lines) and equal to 0.0189 (full lines): from Node 1 to Node 4

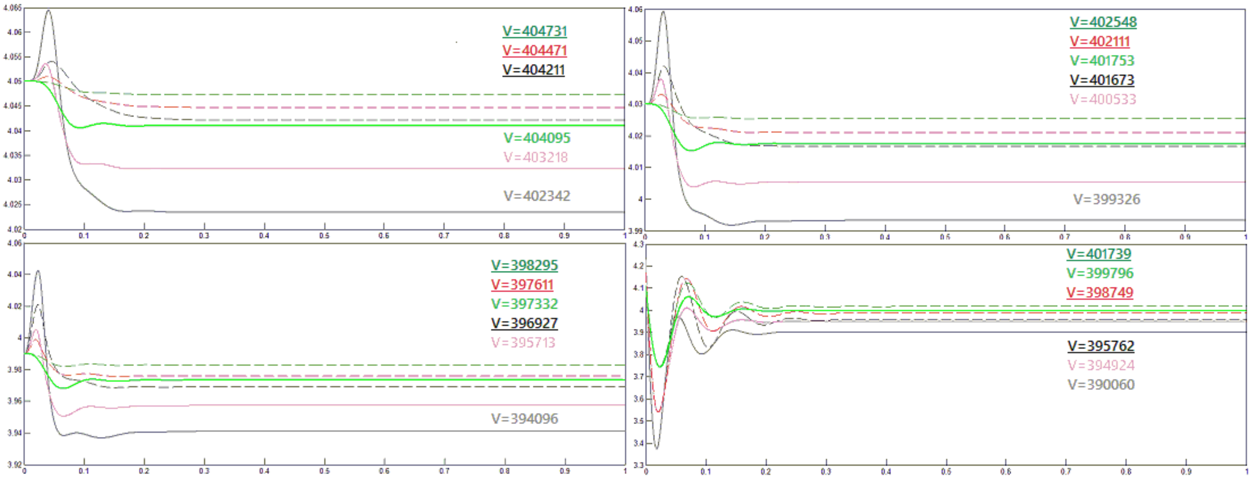


Figure 3.54: Evolution of Voltages in the first period with different references and value of control action equal to 0.041 (dashed lines) and equal to 0.0189 (full lines): from Node 5 to Node 8

Whit the proportional vale equal to 0.041, in the nodes 1, 2 and 3 there is always an oscillatory trend in the third period, but the amplitude and period are higher than the amplitude and the period with the control action with the value of proportional control equal to 0.75. The nodes 5 and 6 have oscillation with little amplitude. The medium value is lower the reference in the same period. Higher is the reference, deeper are the pike in transitory.

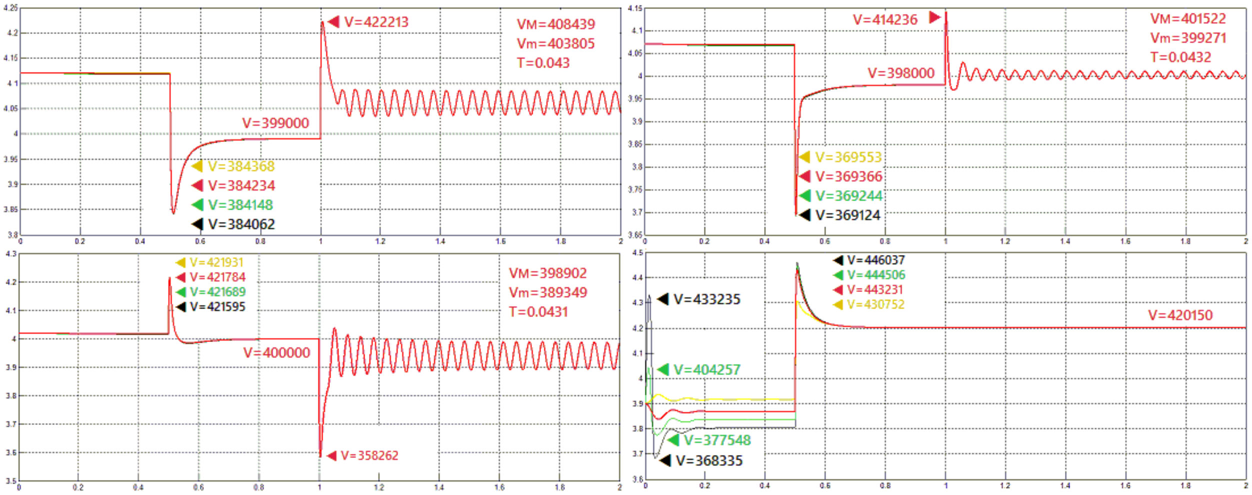


Figure 3.55: Evolution of Voltages in all periods with different references and value of control action equal to 0.041: from Node 1 to Node 4

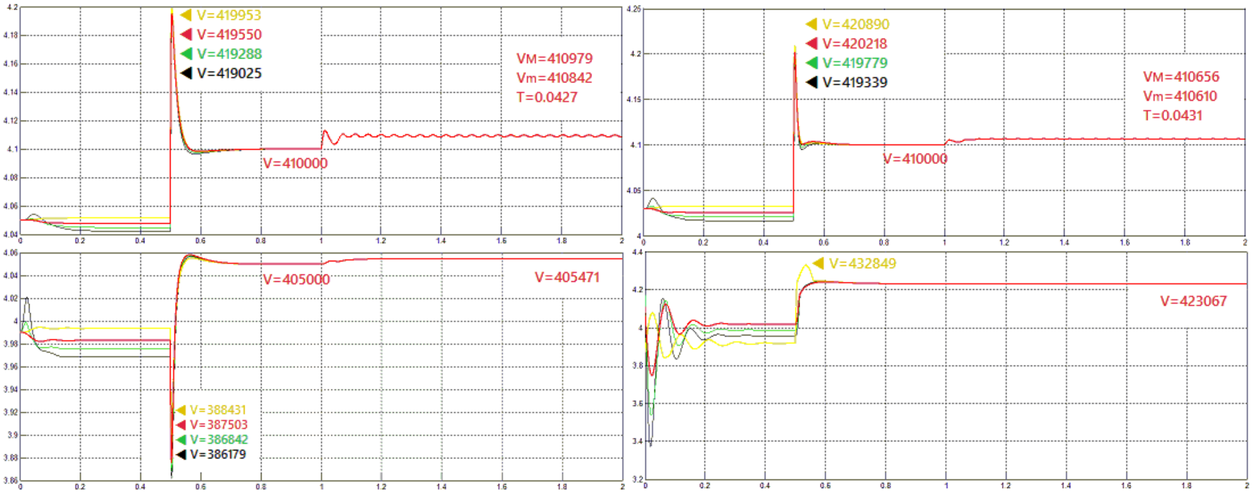


Figure 3.56: Evolution of Voltages in all periods with different references and value of control action equal to 0.041: from Node 5 to Node 8

With the proportional action with value 0.0189, the oscillation in the period of every nodes vanish. The voltages of the nodes follow the references in the second period. Instead, The voltages in the third period, after an oscillating transitory, don't follow the reference. These values are lower then the references. The pikes of the transitory of nodes 3 and 4 go out the admissibility region.

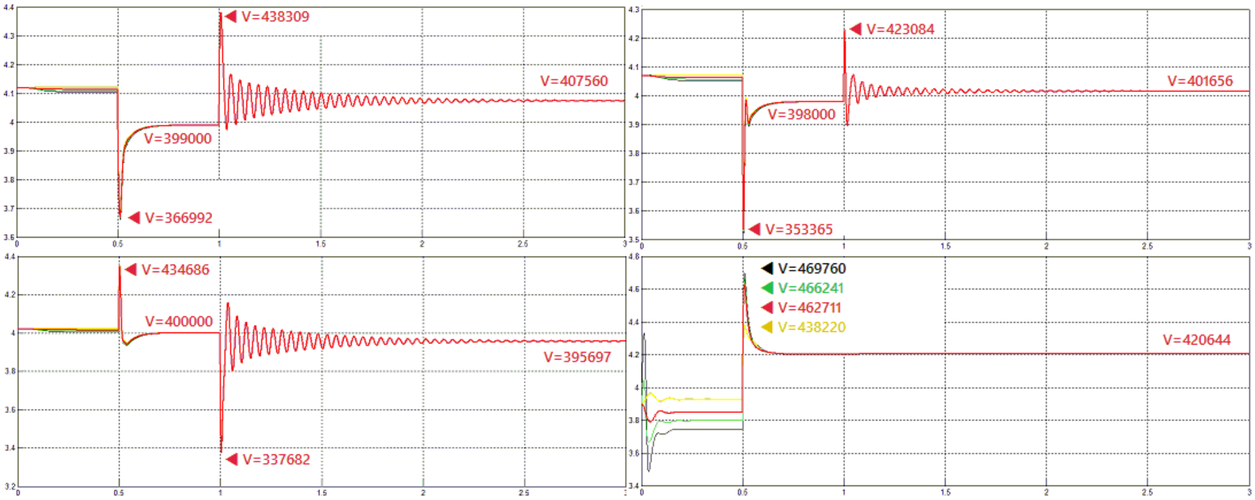


Figure 3.57: Evolution of Voltages in all periods with different references and value of control action equal to 0.0189: from Node 1 to Node 4

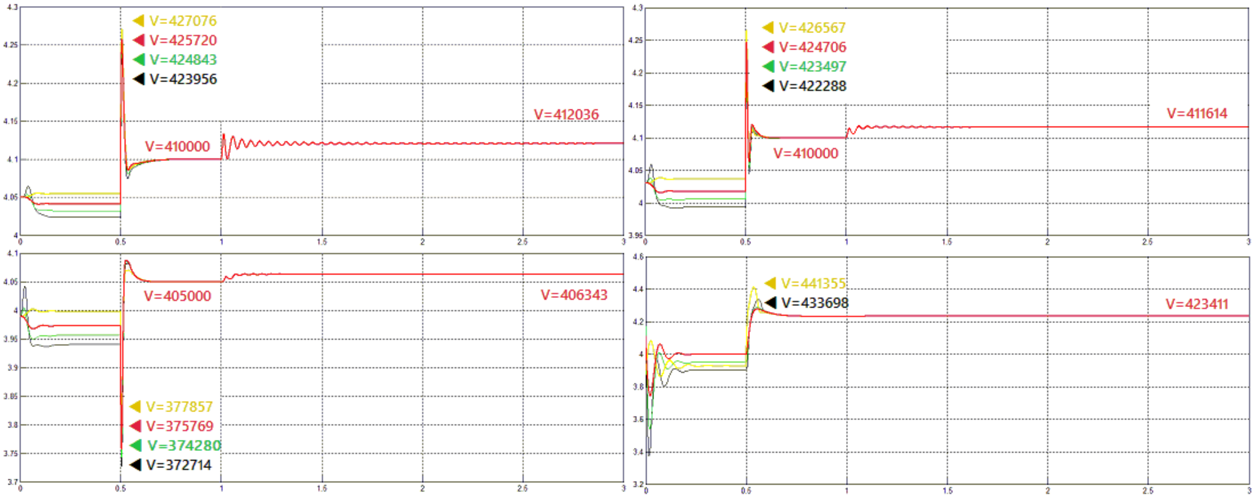


Figure 3.58: Evolution of Voltages in all periods with different references and value of control action equal to 0.0189: from Node 5 to Node 8

3.2.0.3 Node 2

The study of the behavior of the change of the references of node 2 is divide in two case. In both case the references is out of the admissibility region, but in the first case, the references have a value of voltages and current higher than the maximum value of power and current. In the second case, the voltages and currents of the references are lower than the minimum value of current and power for the nodes.

The Figure 3.59 show the behavior of node 2 in the first case.

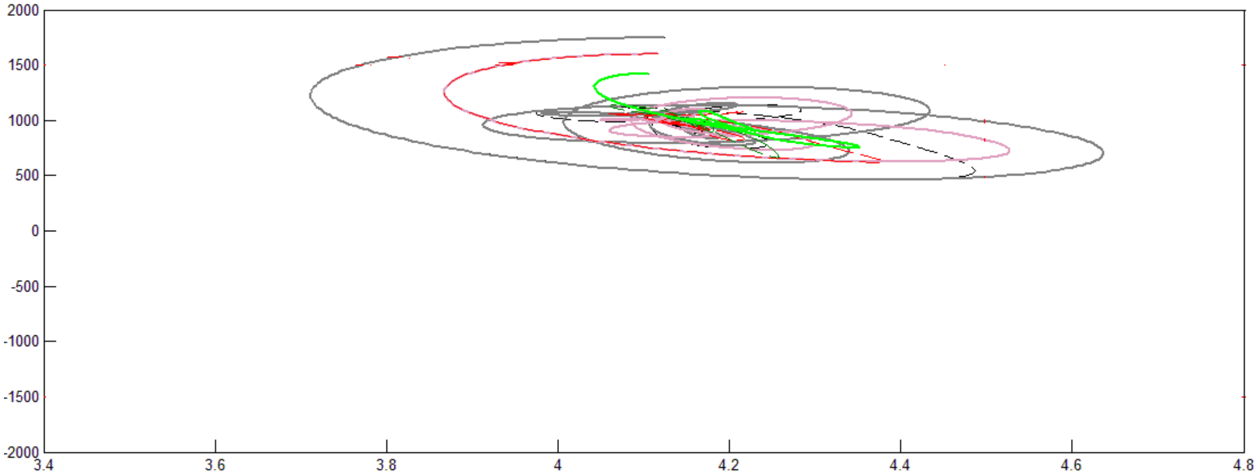


Figure 3.59: Evolution of state variables of Node 2 with action control equal to 0.041 (dashed lines) and equal to 0.0189 (full lines)

In Figure 3.60 is possible to see the different start points of the node 2. Especially for the higher values of the references, the node have oscillation in voltage and current.

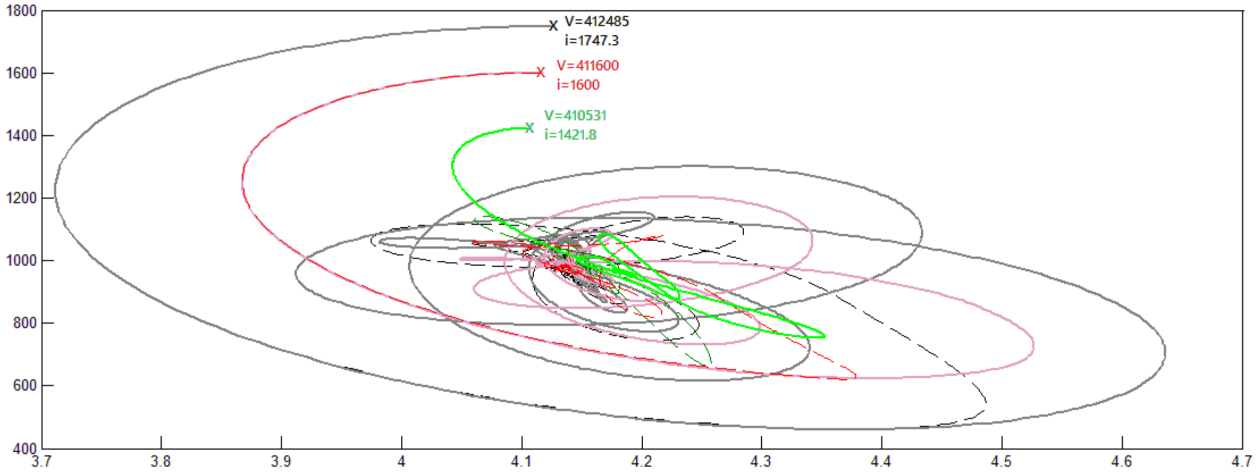


Figure 3.60: Equilibrium point of Node 2

Only in the case of the lower reference, the voltages don't have an oscillatory behavior. The start points of the Node 1, 2 and 3 are different because are different the references of node 2.

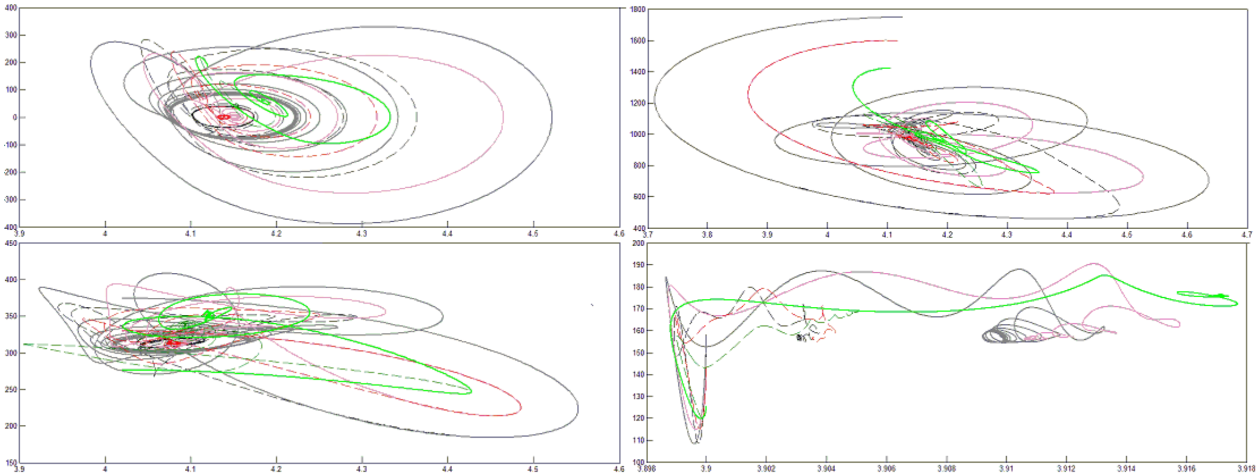


Figure 3.61: Evolution of state variables in the first period with different references and value of control action equal to 0.041 (dashed lines) and equal to 0.0189 (full lines): from Node 1 to Node 4

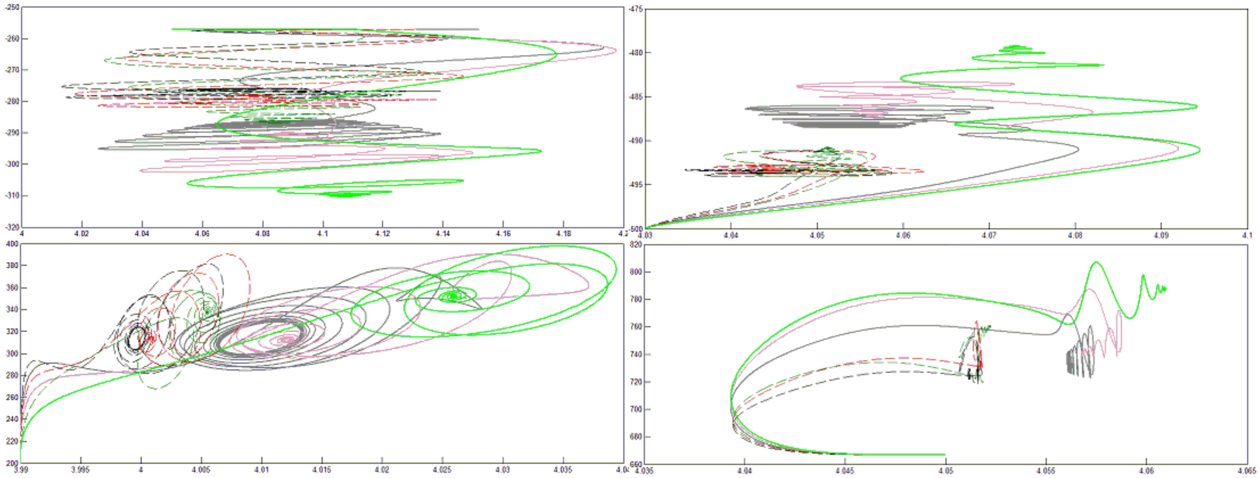


Figure 3.62: Evolution of state variables in the first period with different references and value of control action equal to 0.041 (dashed lines) and equal to 0.0189 (full lines): from Node 5 to Node 8

With a value of reference equal to 410531, the voltages don't have oscillation. Lower is the value of the control, higher are the values of voltages at 0.5 seconds. Higher is the reference, higher are the amplitude and the period of the oscillation in each nodes. With a value of the control high, the influence on the other nodes is lower than the control value is low. Infacts, the full lines have big variation.This behavior is more accentuated in the far nodes, like node 4 and 8.

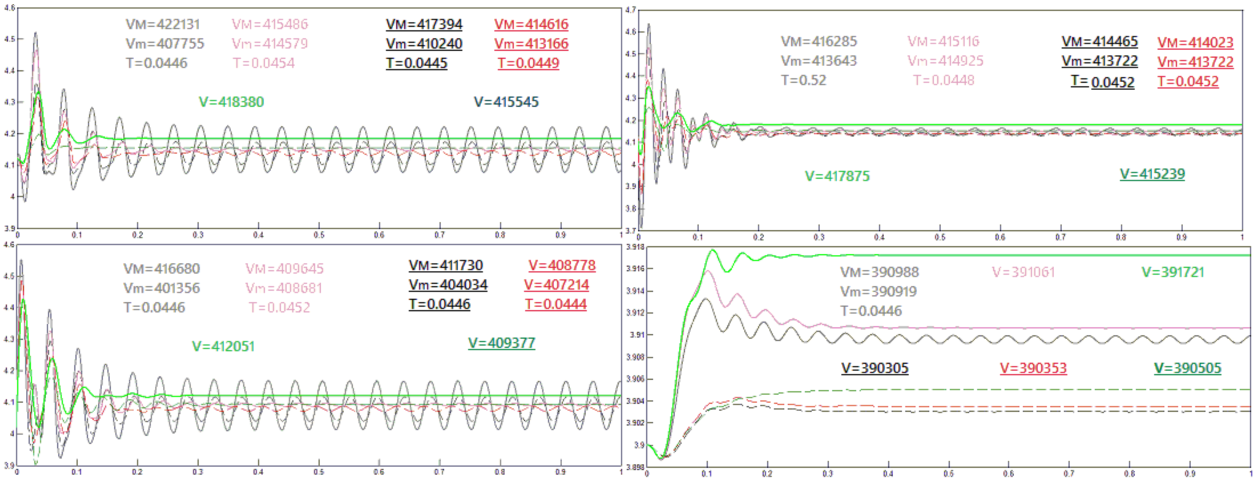


Figure 3.63: Evolution of Voltages in the first period with different references and value of control action equal to 0.041 (dashed lines) and equal to 0.0189 (full lines): from Node 1 to Node 4

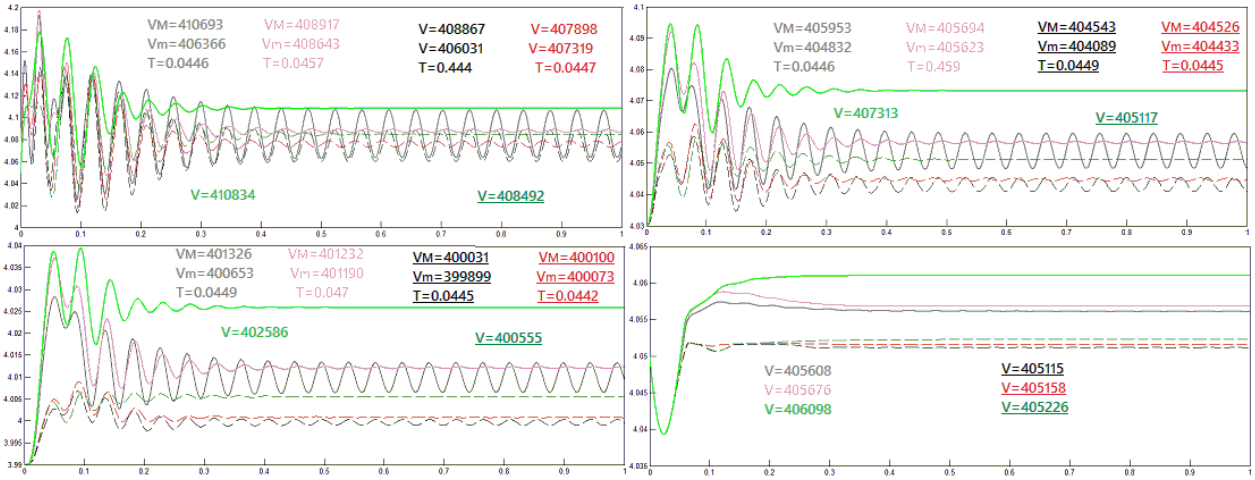


Figure 3.64: Evolution of Voltages in the first period with different references and value of control action equal to 0.041 (dashed lines) and equal to 0.0189 (full lines): from Node 5 to Node 8

As in the other case, the variation of the action control leads an oscillatory behavior in the third period, Figure 3.65 and 3.66.

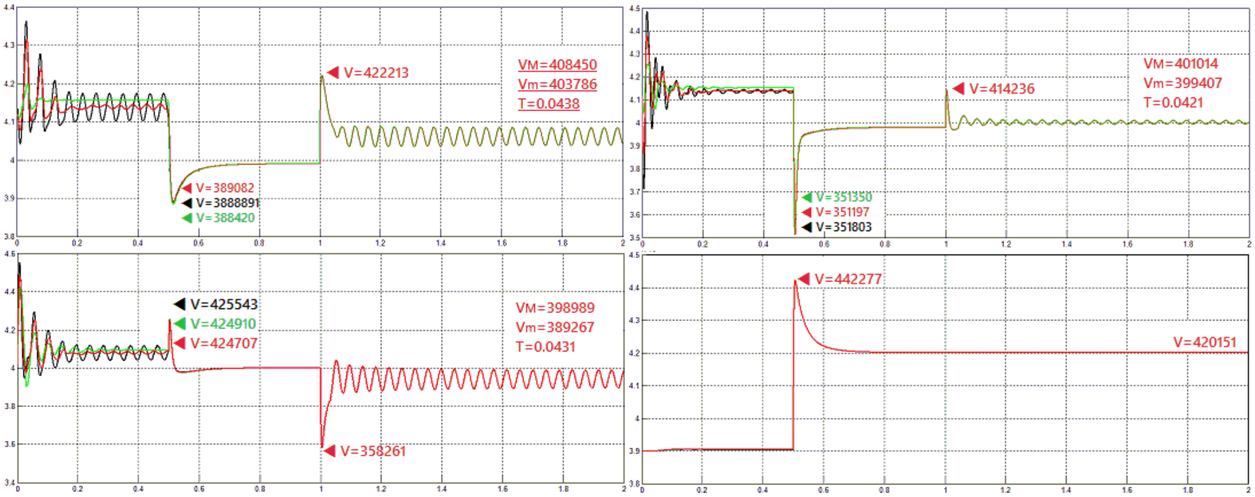


Figure 3.65: Evolution of Voltages in all periods with different references and value of control action equal to 0.041: from Node 1 to Node 4

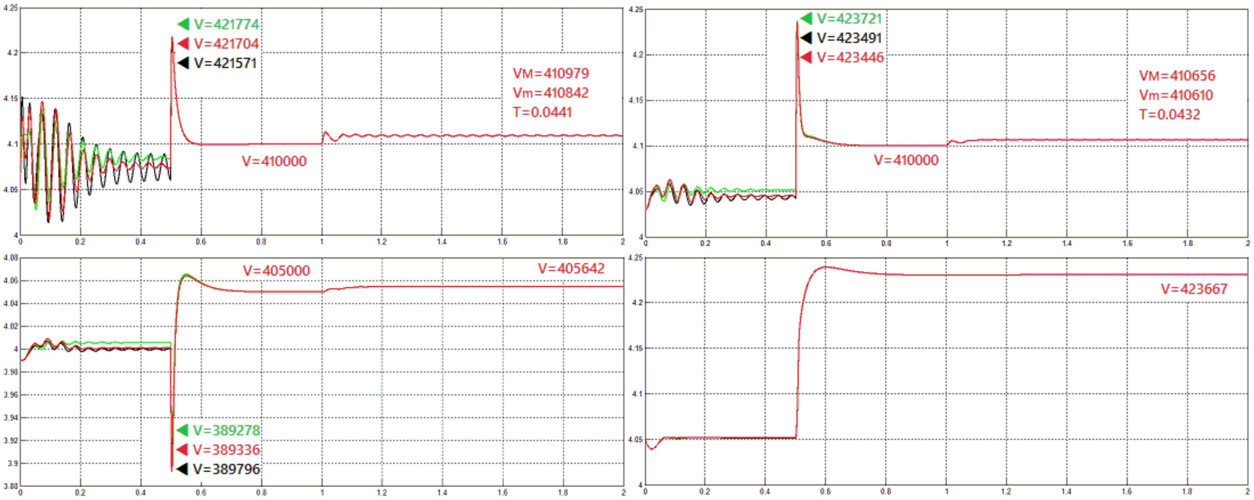


Figure 3.66: Evolution of Voltages in all periods with different references and value of control action equal to 0.041: from Node 5 to Node 8

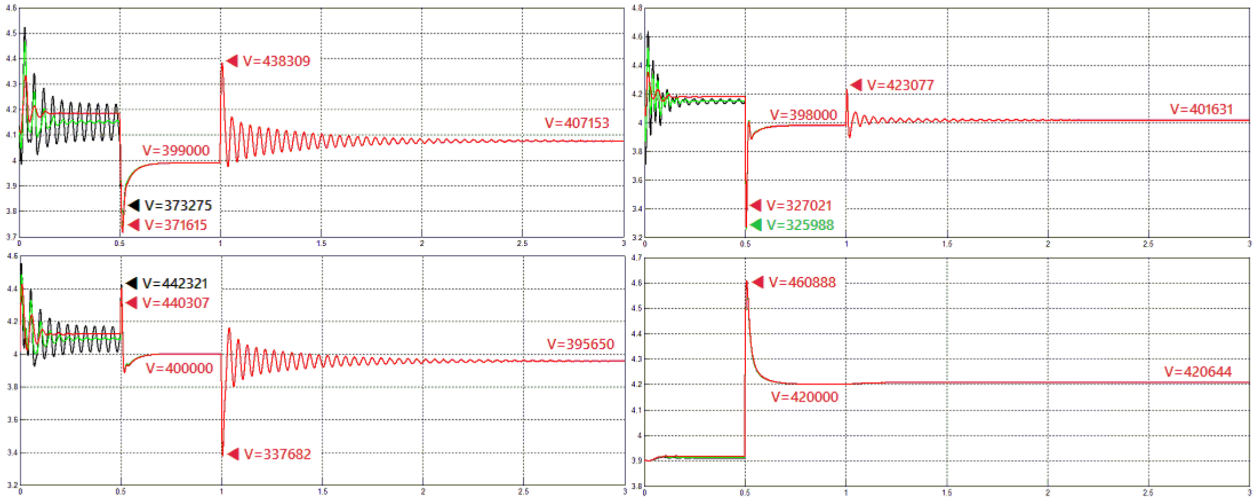


Figure 3.67: Evolution of Voltages in all periods with different references and value of control action equal to 0.0189: from Node 1 to Node 4

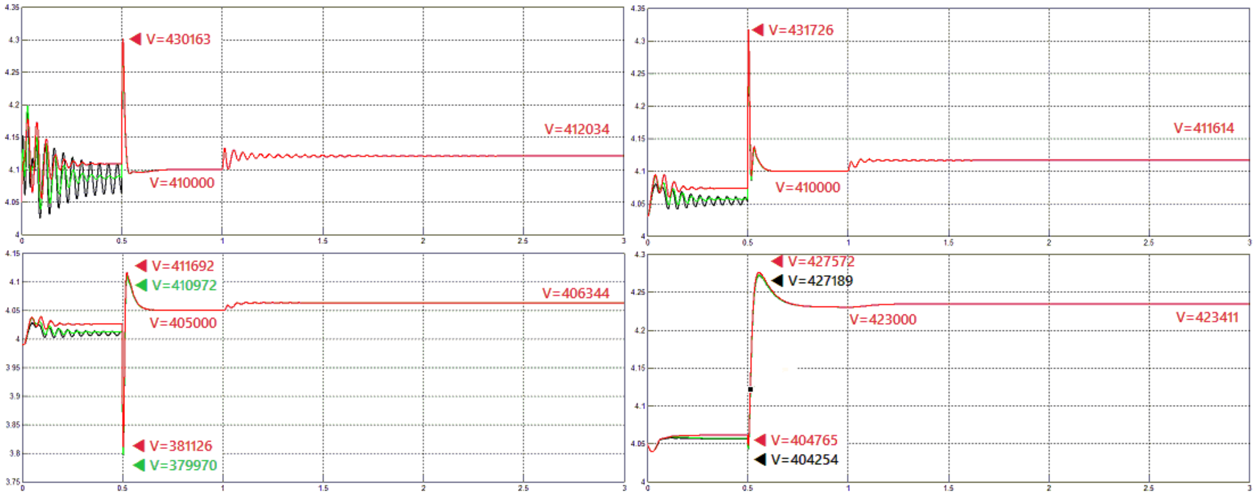


Figure 3.68: Evolution of Voltages in all periods with different references and value of control action equal to 0.0189: from Node 5 to Node 8

The Figure 3.69 show the different case when the references are lower than the minimum value of power and current of the admissibility region. In this case the start points are different.

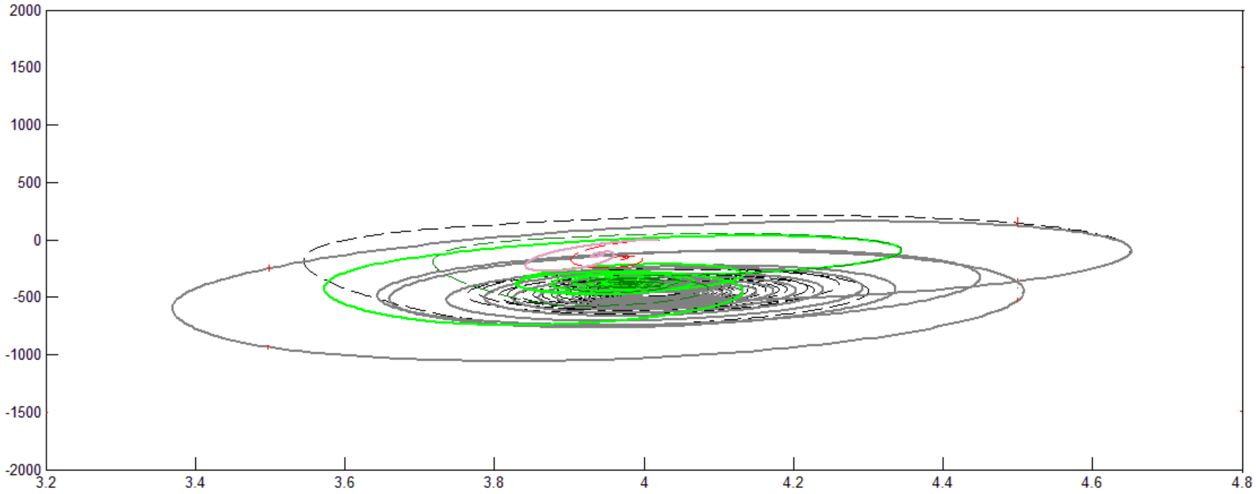


Figure 3.69: Evolution of state variables of Node 2 with action control equal to 0.041 (dashed lines) and equal to 0.0189 (full lines)

When the references of the node 2 are different, also the initial points of the node 1, 3 and 4 are different. In particular, the voltages are the same, but the currents depend on the values of the references.

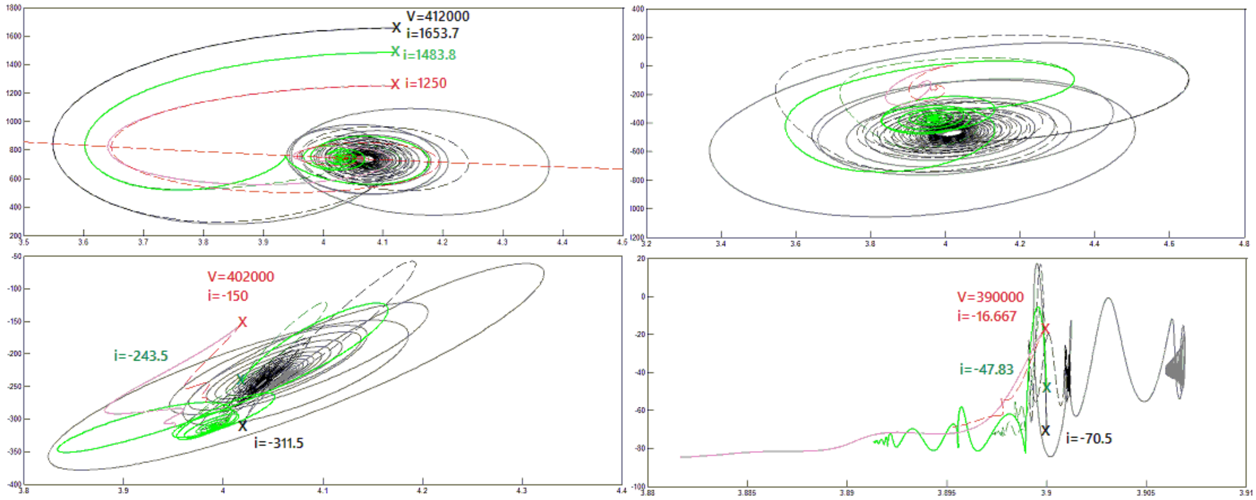


Figure 3.70: Evolution of state variables in the first period with different references and value of control action equal to 0.041 (dashed lines) and equal to 0.0189 (full lines): from Node 1 to Node 4

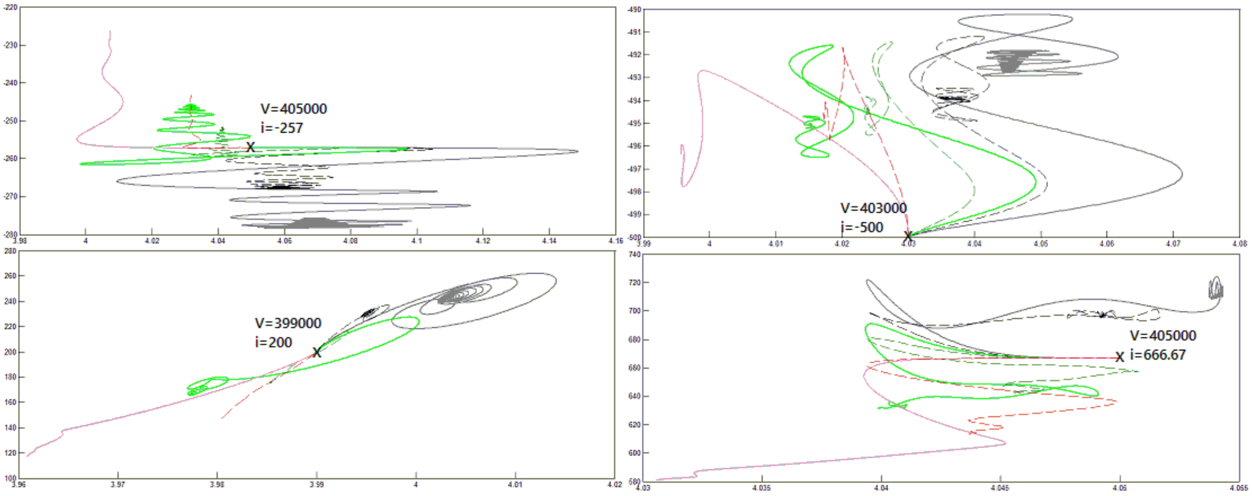


Figure 3.71: Evolution of state variables in the first period with different references and value of control action equal to 0.041 (dashed lines) and equal to 0.0189 (full lines): from Node 5 to Node 8

The Figure 3.72 and 3.73 show the evolution of the voltages with different references and different values of the control action. Only in the case of the black lines there are oscillations. higher is the control action, lower is the amplitude and the period of the oscillation. It's the same case with the other references, but there aren't oscillation. The influence of the references on the other nodes is higher when the the value of the control action is low. In facts,the voltages of Node 4 and 8, who are nodes far from the node 2, don't follow the reference of the nodes. Lower is the reference of node 2, lower is the value of the voltages at 0.5 seconds. In that way, the voltages don't follow the references.

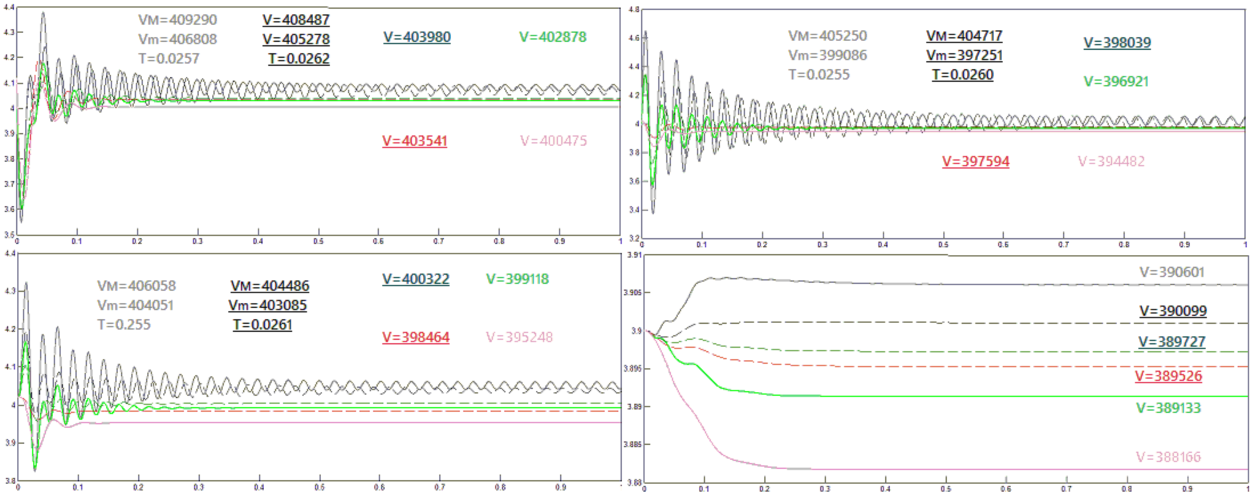


Figure 3.72: Evolution of Voltages in the first period with different references and value of control action equal to 0.041 (dashed lines) and equal to 0.0189 (full lines): from Node 1 to Node 4

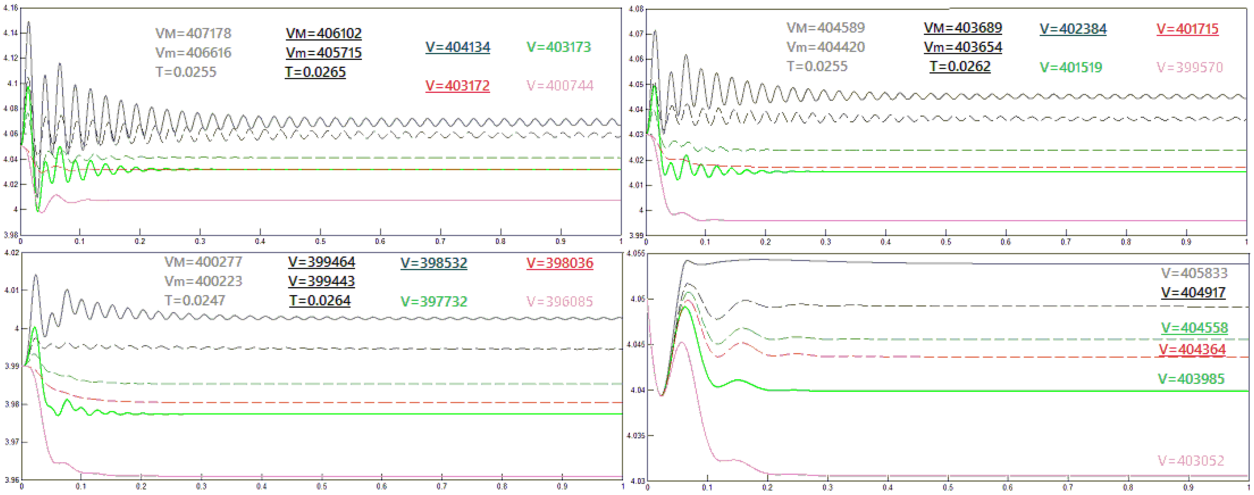


Figure 3.73: Evolution of Voltages in the first period with different references and value of control action equal to 0.041 (dashed lines) and equal to 0.0189 (full lines): from Node 5 to Node 8

The oscillatory trend, in the third period, is present only when the value of the control action is equal to 0.041. When that value is equal to 0.0189, the voltages reach an equilibrium point lower than the reference of each nodes.

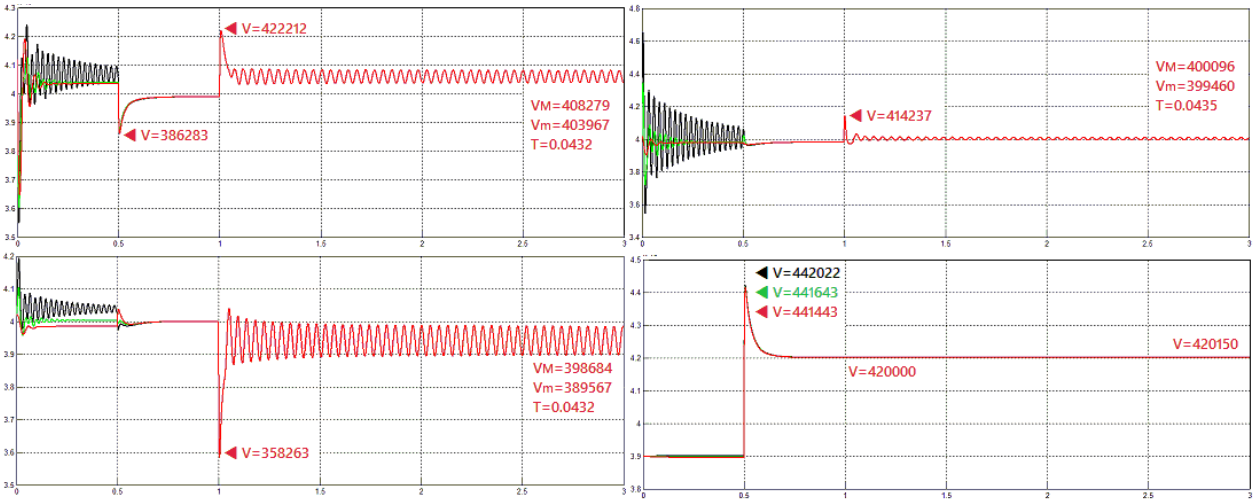


Figure 3.74: Evolution of Voltages in all periods with different references and value of control action equal to 0.041: from Node 1 to Node 4

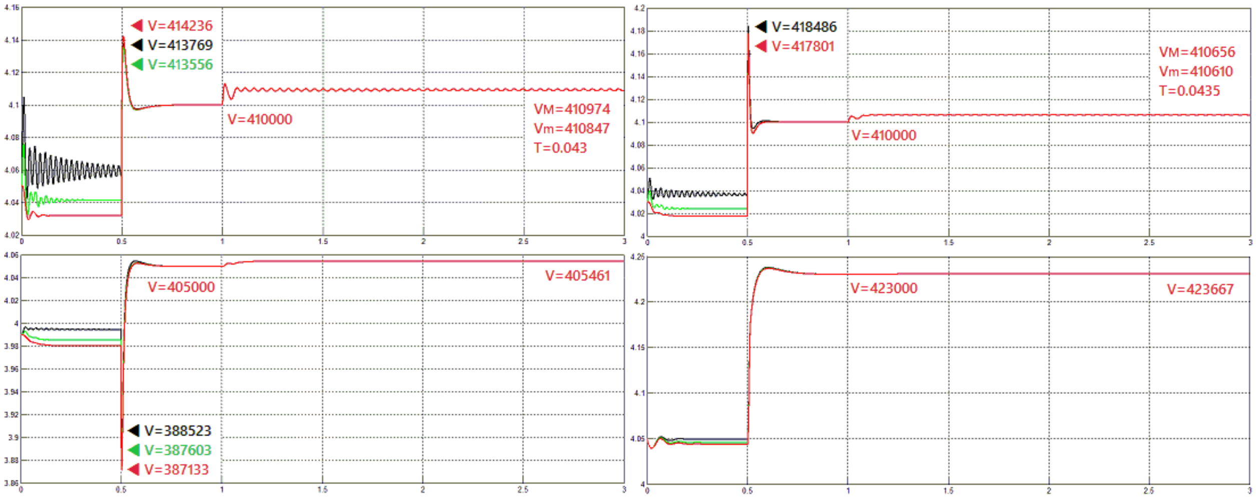


Figure 3.75: Evolution of Voltages in all periods with different references and value of control action equal to 0.041: from Node 5 to Node 8

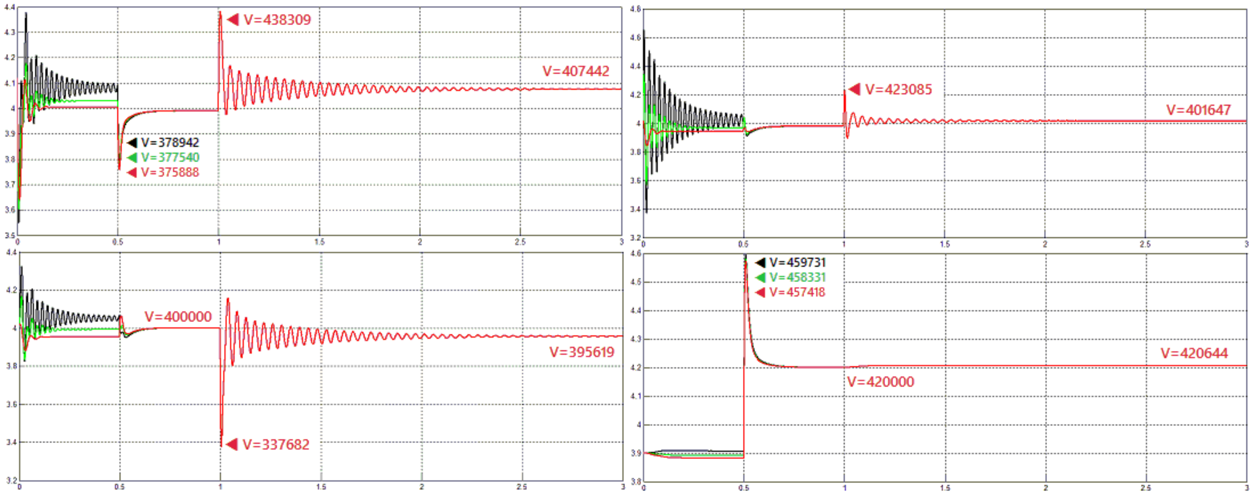


Figure 3.76: Evolution of Voltages in all periods with different references and value of control action equal to 0.0189: from Node 1 to Node 4

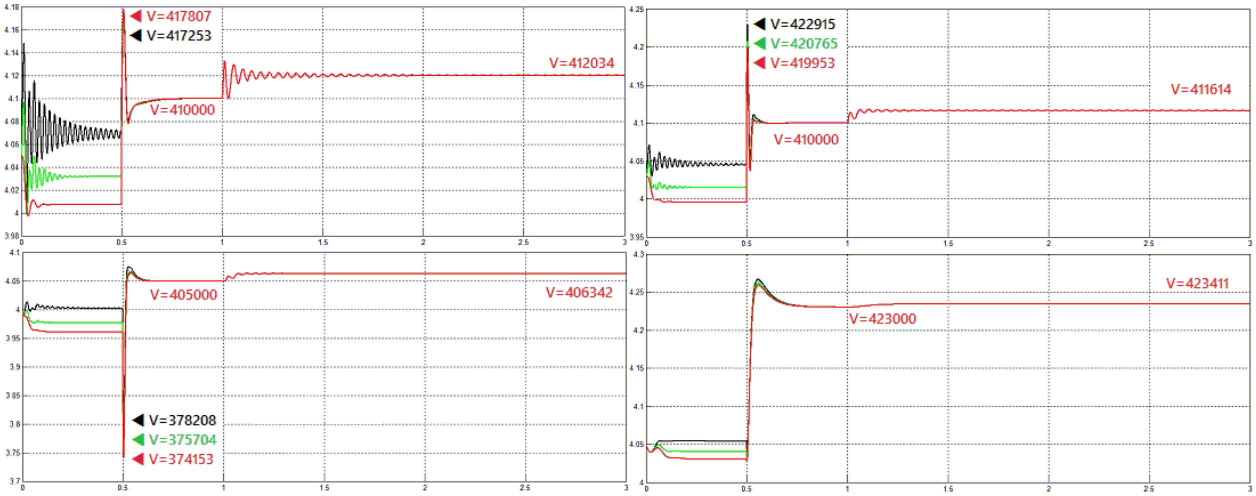


Figure 3.77: Evolution of Voltages in all periods with different references and value of control action equal to 0.0189: from Node 5 to Node 8

Chapter 4

PI Control

The possible outcomes of the system will be examined, when the PI control is in use. Comparison between the two different types of control will be -made, in order to assess which one is ideal for this type of analysis. The evolution of the system has been monitored and divided in three time lapses of 0.5 seconds each. For each time lapse, the nodes have different references. However, the research that has been made shows the changes in references just for the first time lapse, which extends from zero to 0.5 seconds.

4.1 Reference inside the region; compare with P control

This chapter show the behavior of system when the control is a PI. The integral action is obtained trough the Ziegler-Nichols condition. In this way, with integral action, the system become more stable and vanish the oscillatory trend that present with only the proportional action. The first study is when the PI control is applied to the system that have the reference of each node into their admissibility region. In this way it's possible to compare with the only proportional control. Figure 4.1 show the evolution of all nodes when the action control is a PI. The values of the proportional and integral actions are calculated by the Ziegler-Nichols condition. This control action has important variation in the evolution of all nodes, because the nodes 1, 2 and 3 don't have the oscillatory trend after 1 seconds. In each period, the voltages of all nodes follow their references. For this reason, the application of the PI control gives to the system greater precision. The voltages of nodes 3 and 4 go out the admissibility region. In particular, the pike in the transitory in the third period of node 3 and the pike of the transitory in the second period of node 4 go out of their admissibility region.

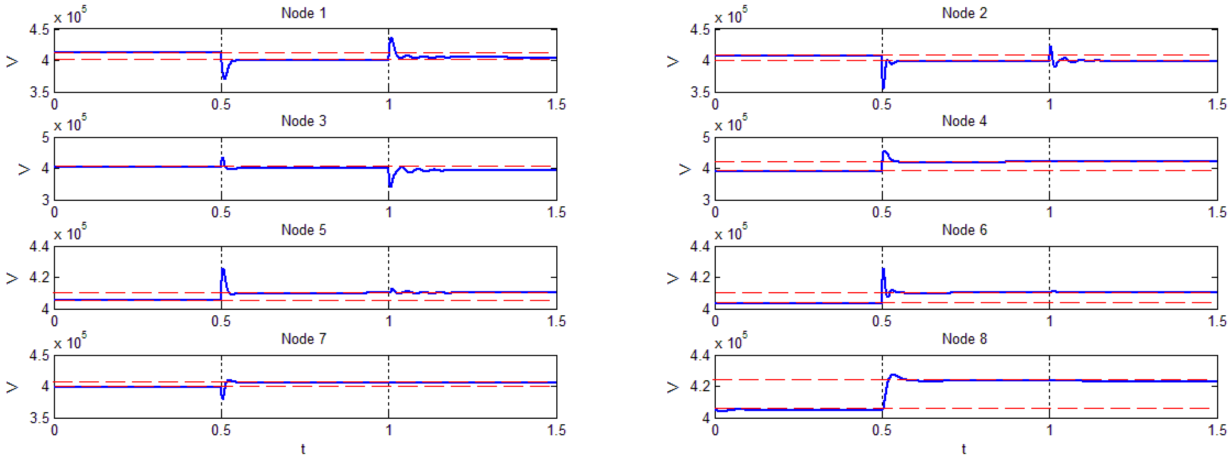


Figure 4.1: Voltages of each Nodes

As possible to see in the Table 2.1, the values of the voltage of each nodes are the same of the references except for the Node 1 and Node 3, where the value is not the same in the third period.

K	sec	1	2	3	4
		412000	407000	402000	390000
	0.5	412000	407000	402000	390000
		399000	398000	400000	420000
0.0189	1	399000	398000	400000	420000
		405000	398000	390000	420000
	1.5	403940	398000	391875	420000

K	sec	5	6	7	8
		405000	403000	399000	405000
	0.5	405000	403000	399000	405000
		410000	410000	405000	423000
0.0189	1	410000	410000	405000	423000
		410000	410000	405000	423000
	1.5	410000	410000	405000	423000

Table 4.1: Value of Voltage

The Figure 4.2 and Figure 4.3 Show the behavior of each nodes in a graph Voltage-Current. In these case the voltage of the Node 4 go out of the admissibility region of voltage in the second period. The same behavior is possible to see in the Node 3, where the voltage become lower then 350000 V who represent the minimum value for the voltage. This kind of behavior is not possible to see in the system with P control.

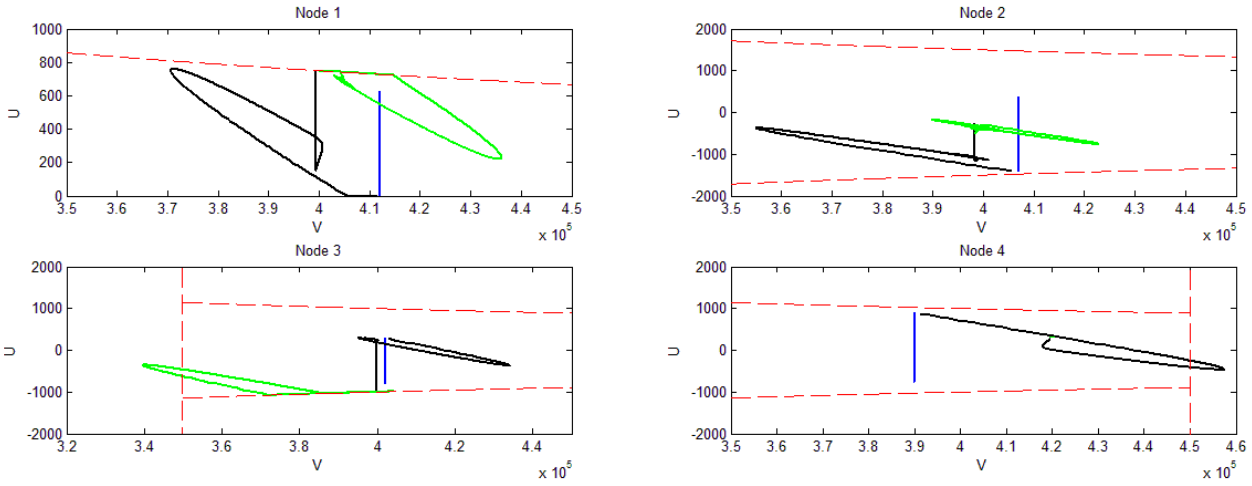


Figure 4.2: Evolution of Nodes from 1 to 4

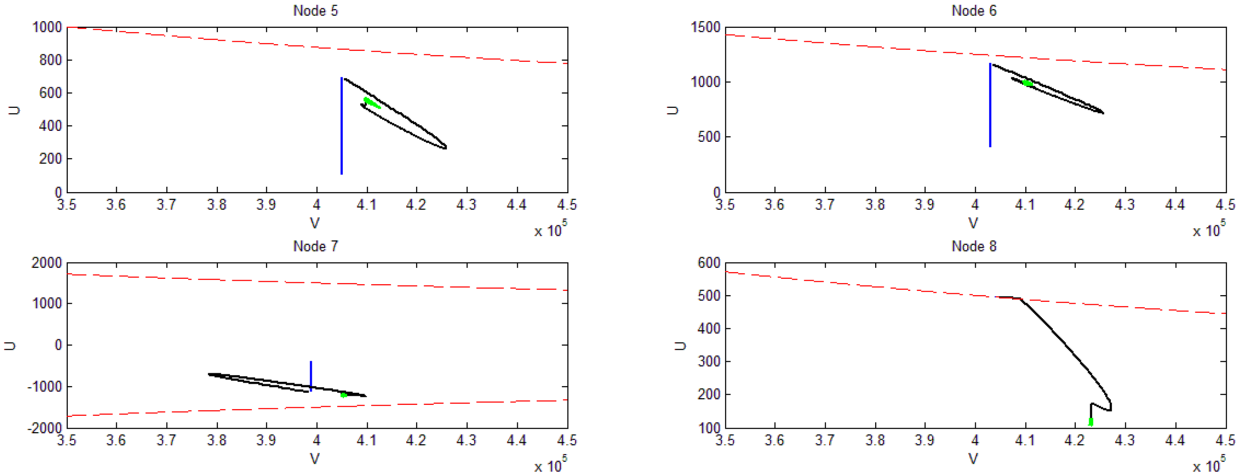


Figure 4.3: Evolution of Nodes from 5 to 8

4.2 Reference outside the region

This section of the paper study the application of the PI control when the start condition of some nodes are out of their admissibility region. Also in this case, there are different between nodes: pour of connection and nodes with more connection. Node 1 and Node 8 be part of the first categories while Node 2 belong to the second categories.

4.2.1 Node pour of connection

4.2.1.1 Node 1

All the references of the nodes 1 are out the admissibility region. The equilibrium points are situated on the line who represent the maximum power for the node 1. The X in Figure

4.4 represent the initial points with different references. The lines in black and green start out of the admissibility region. The values of the current of both lines are higher then the maximum value of the current in node 1. The blue and red lines start from a points higher the maximum power of node 1 but lower the maxim value of the current. The yellow line starts out of the admissibility region. It's start point is lower then the minimum value of current of node 1.

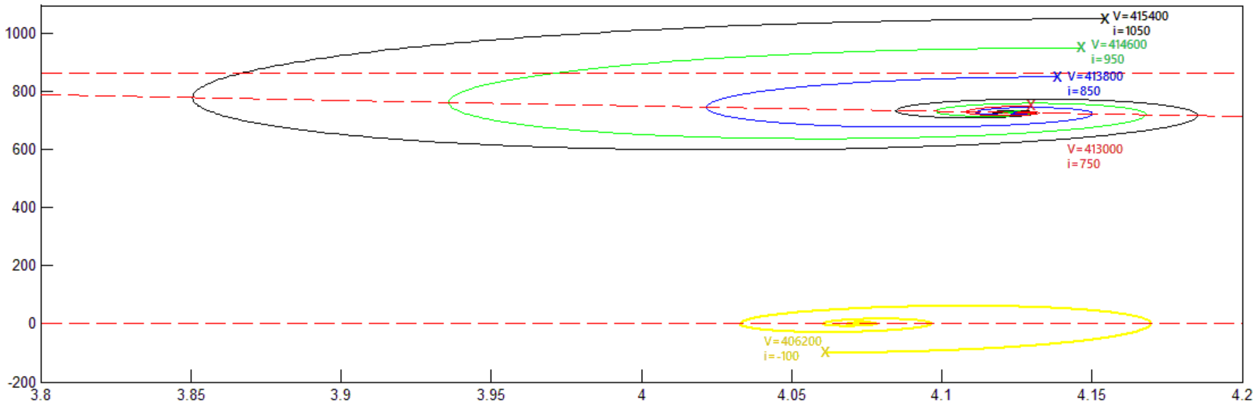


Figure 4.4: Admissibility region Node 1

The Figure 4.5 show the equilibrium points for the different references. There is a little distance between the equilibrium points. This distance is higher then the distance between the references.

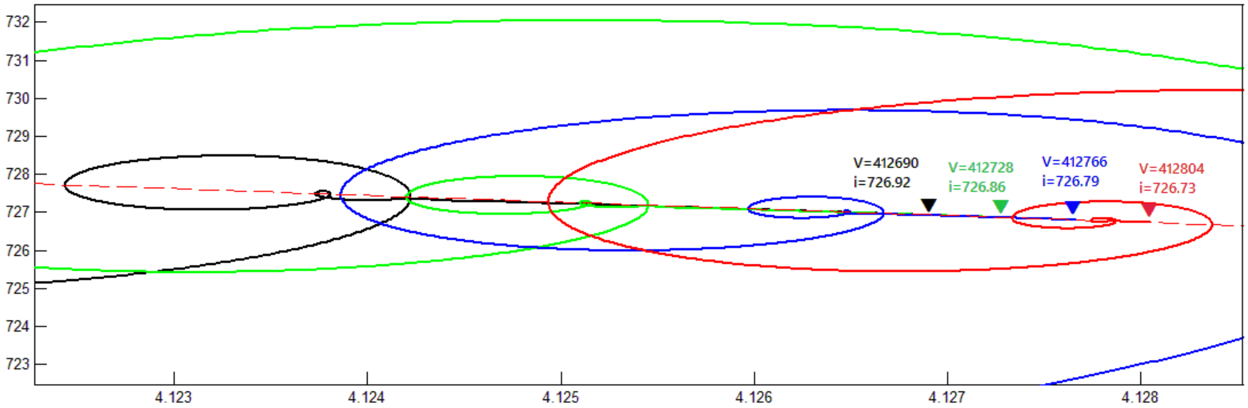


Figure 4.5: Equilibrium points of Node 1

The other nodes have the equilibrium point near their references. Further are the nodes, lower is the influence. In this case of control, the other nodes don't are affected by the change of the references of node 1. In facts the node 2 has a variation of the voltages more little. The difference between the equilibrium points from different references is more little then the variation of the references. The Voltages of node 2has a variation of 125 V. The Node 3 has a variation of 90 V. This is a demonstration of the lower influence when the nodes are further. Node 4 and 8 don't have variation in the equilibrium points. In this way , the voltages at 0.5 seconds is equal to the references at the same time. In general, every nodes follow the references at 0.5 seconds.

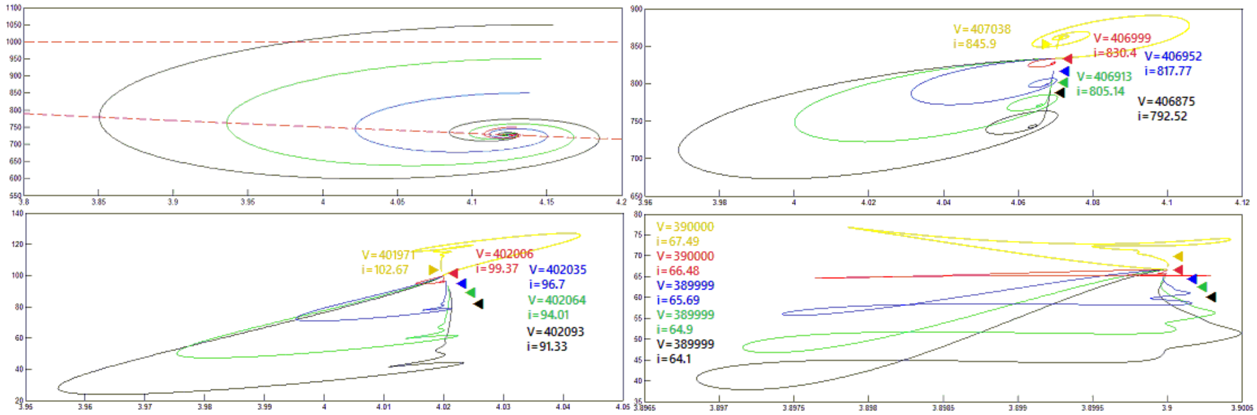


Figure 4.6: Evolution of state variables in the first period with different references and PI control: from Node 1 to Node 4

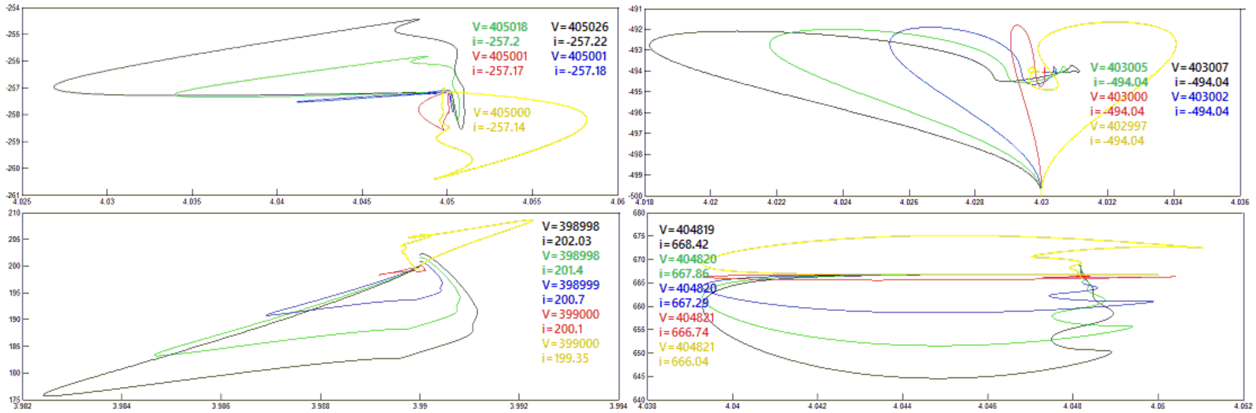


Figure 4.7: Evolution of state variables in the first period with different references and PI control: from Node 5 to Node 8

The evolution of the voltages of nodes are presented in Figure 4.8 and 4.9. Only node 1 has the value of the voltage not equal to the reference at 0.5 second. All the other nodes follow their references. The variation of the reference of the Node 1 leads an under elongation in the transitory. Higher is the reference, deeper is the elongation. Further are the nodes, lower is the influence. In fact, the pikes of the under elongation of the nodes nearest the node 1 are deeper then the nodes further the node 1. Node 2 and 3 are more affected then the node 5 and 6. Node 4 and 8 have a little variation. When the reference of the node 1 is under the admissibility region, there isn't under elongation but upper elongation.

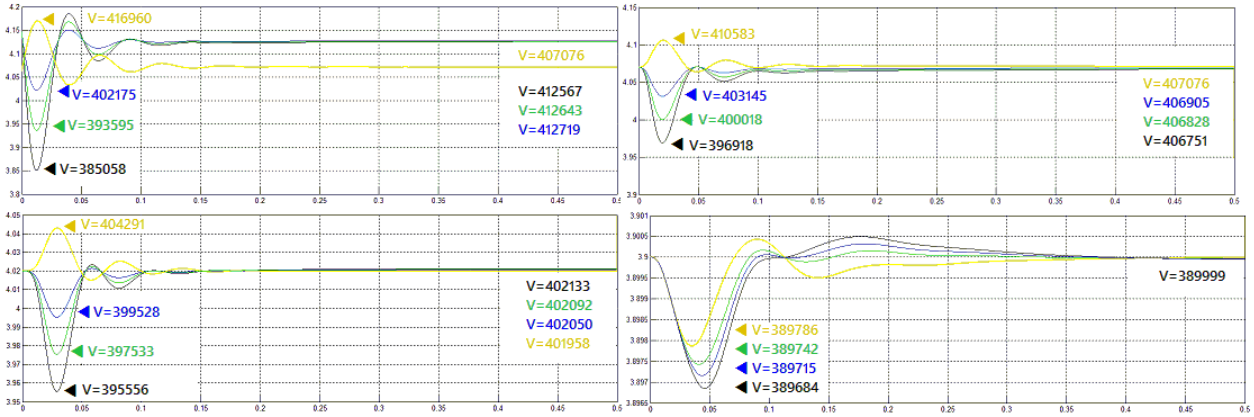


Figure 4.8: Evolution of Voltages in the first period with different references and PI control: from Node 1 to Node 4

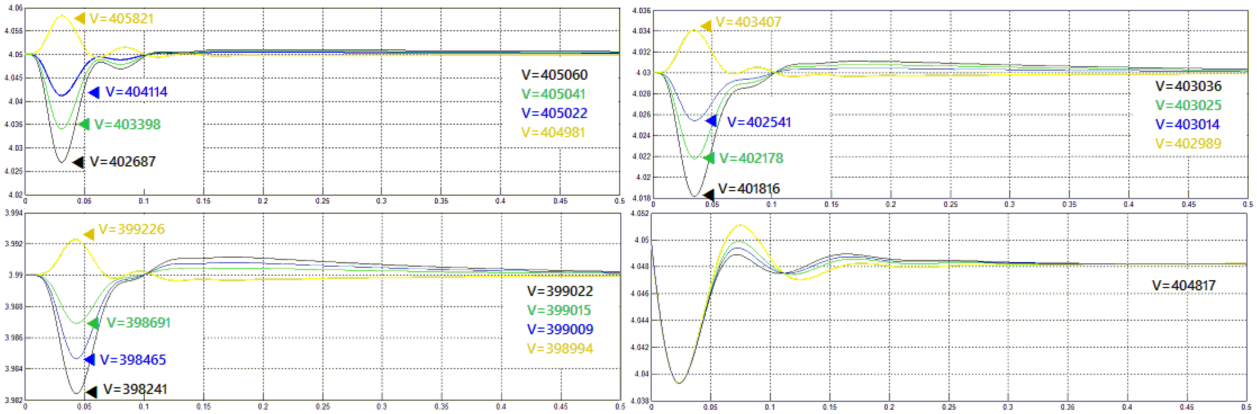


Figure 4.9: Evolution of Voltages in the first period with different references and PI control: from Node 5 to Node 8

The Figure 4.10 and 4.11 show the evolution of all nodes in three different period. The blue lines represent the evolution of the state variables in the first period. The black lines represent the evolution in the second period and the green lines third period. The node 1 has the equilibrium points of the first and third period on the line who represent the maximum power for the node.

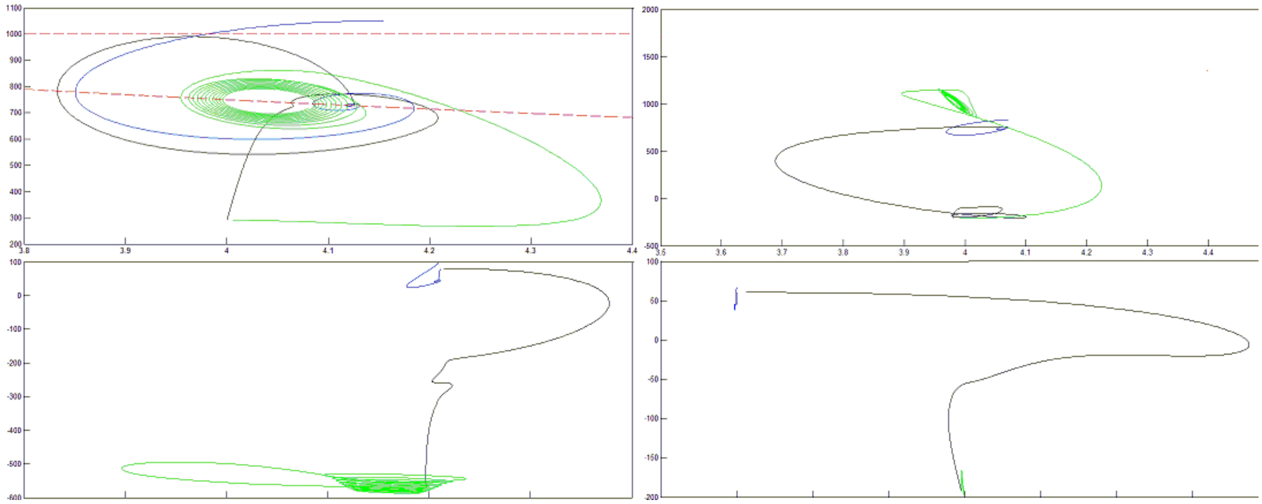


Figure 4.10: Evolution of Voltages in all periods with different references and PI control: from Node 1 to Node 4

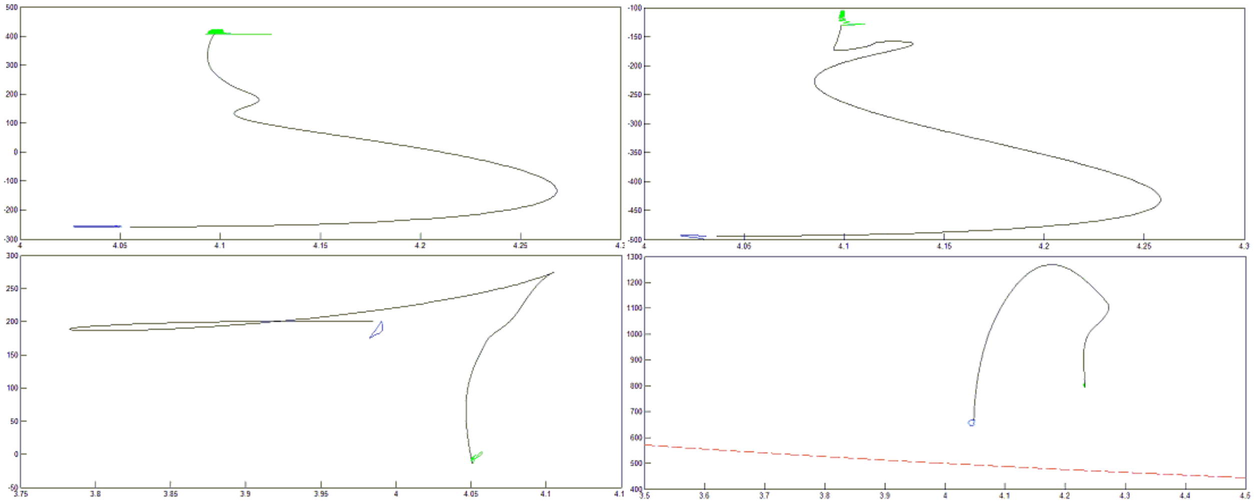


Figure 4.11: Evolution of Voltages in all periods with different references and PI control: from Node 5 to Node 8

The voltages of the nodes with the PI control follow the references in the second and third period. Only the node 1 has the voltage at 1.5 second lower the reference at the same time. In the transitory of all period, there is a pike. In the node 1 and 2, lower are the references, deeper are the pike. The opposite reaction have the other nodes, like node 3, 5 and 6. The far nodes, like node 7, 4 and 8, don't are affected by the variation of the reference of node 1. The pikes don't depend by the values of the reference. It's the same for the values of the voltages at 1 and 1.5 seconds. In the transitory of the third period there is an oscillatory behavior. Higher is the reference, higher are the amplitude and the length of the the oscillatory trend. In facts the blue and yellow line have the minimum value of amplitude and their oscillation vanish before the other lines. Only nodes 4, 7 and 8 don't have oscillation.

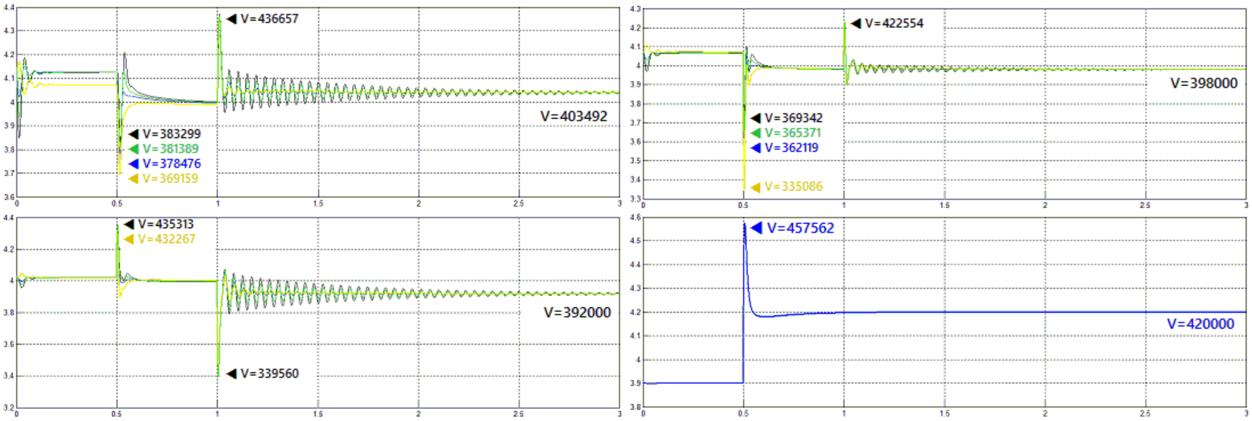


Figure 4.12: Evolution of Voltages in all periods with different references and PI control: from Node 1 to Node 4

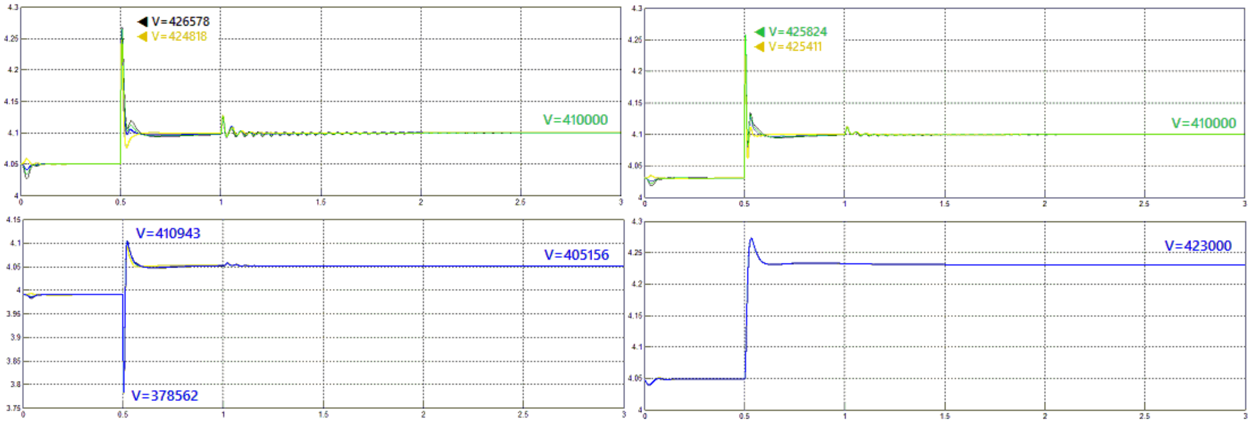


Figure 4.13: Evolution of Voltages in all periods with different references and PI control: from Node 5 to Node 8

4.2.1.2 Node 8

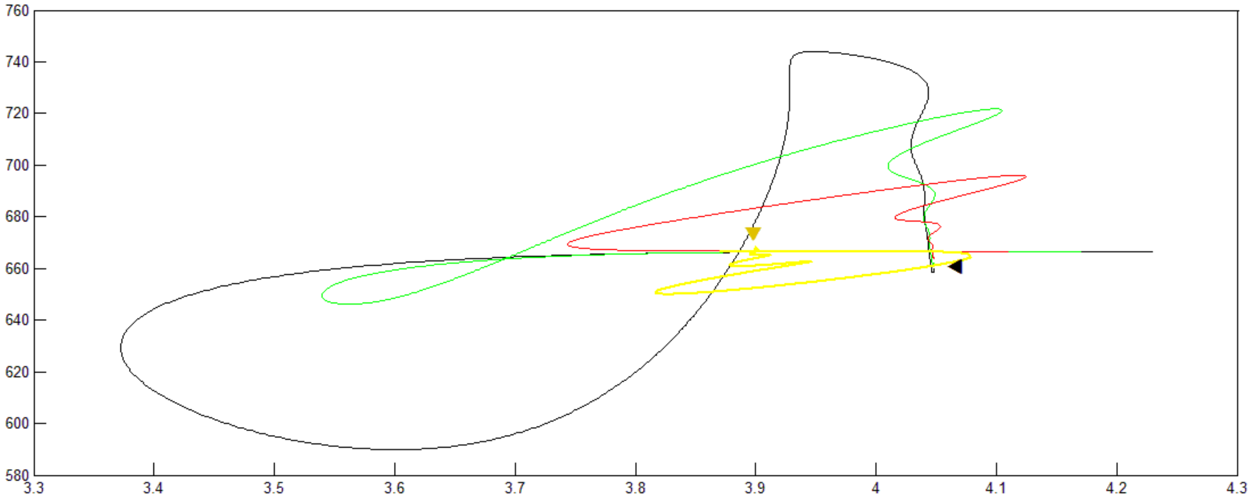


Figure 4.14: Initial condition of Node 8

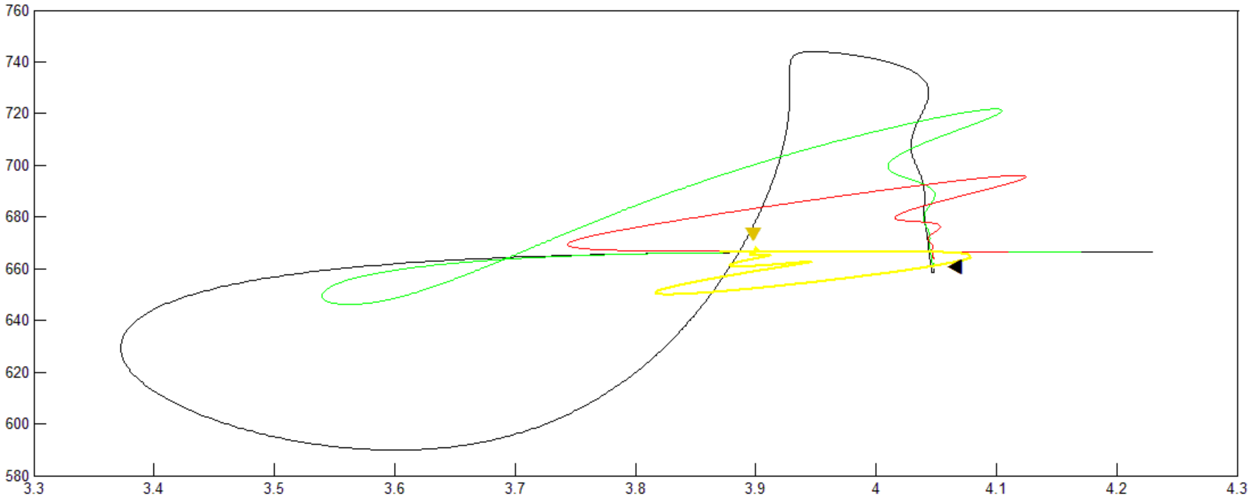


Figure 4.15: Equilibrium points of Node 8

The far nodes from node 8, like nodes 1, 2 and 3, don't are affect by the change of the variation of the reference of node 8. They follow their reference at 0.5 second. The node 4 has the behavior also if is direct connected with node 8. In this case, the evolution of state variables with high values of the references, go out the admissibility region of voltage. In facts, the black line of node 4 have lower value of voltage then the minimum value of the admissibility region. The node 6 have different start points that depend by the references of the node 8. In the end, the influence of the variations of node 8 is lower then the variations of node 1.

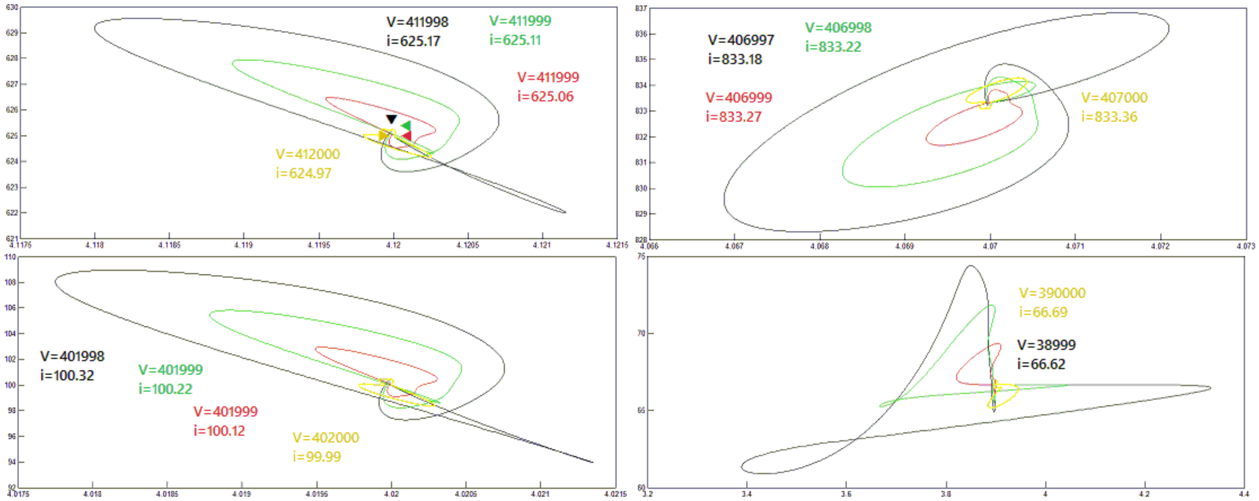


Figure 4.16: Evolution of state variables in the first period with different references and PI control: from Node 1 to Node 4

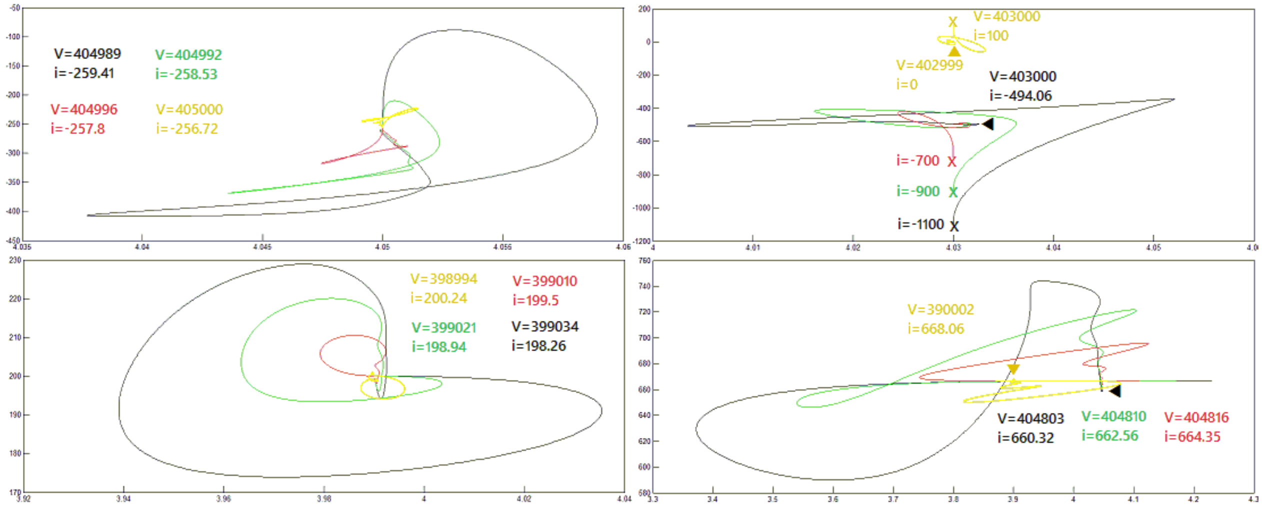


Figure 4.17: Evolution of state variables in the first period with different references and PI control: from Node 5 to Node 8

In the evolution of the voltages in the first period, Figure 4.18 and 4.19, higher are the references, deeper are the pike in the transitory. In the same way, further are the nodes, lower is the influence and lower is the difference between the value of the pikes. In facts, the variations of the pikes are equal to 200/ 300 Volts in the nodes 1, 2 and 3 while in the node 4 the variation is equal to 50000 V. The voltages at 0.5 seconds don't have the same variation. They follow the references.

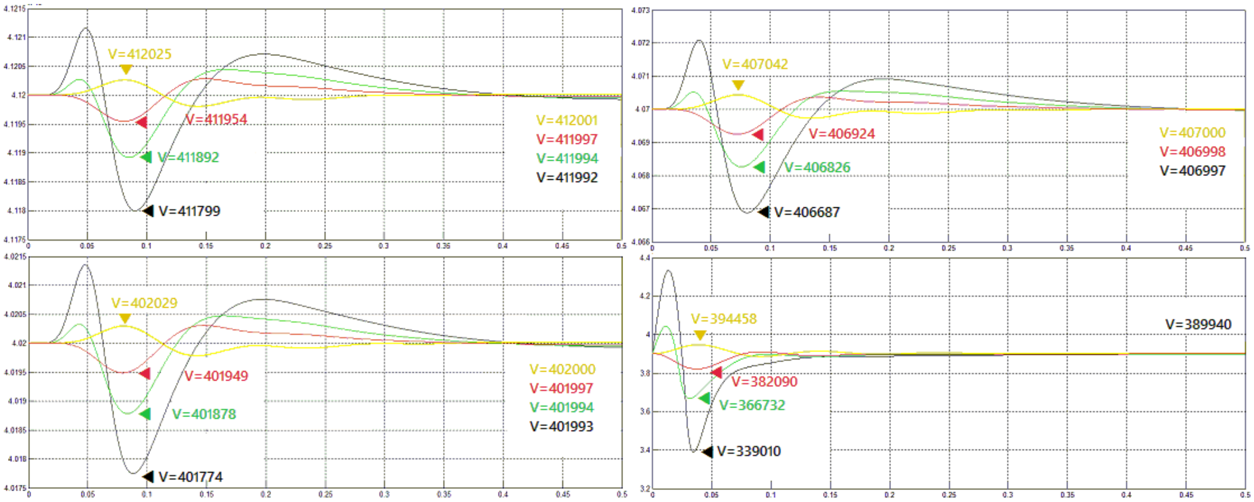


Figure 4.18: Evolution of Voltages in the first period with different references and PI control: from Node 1 to Node 4

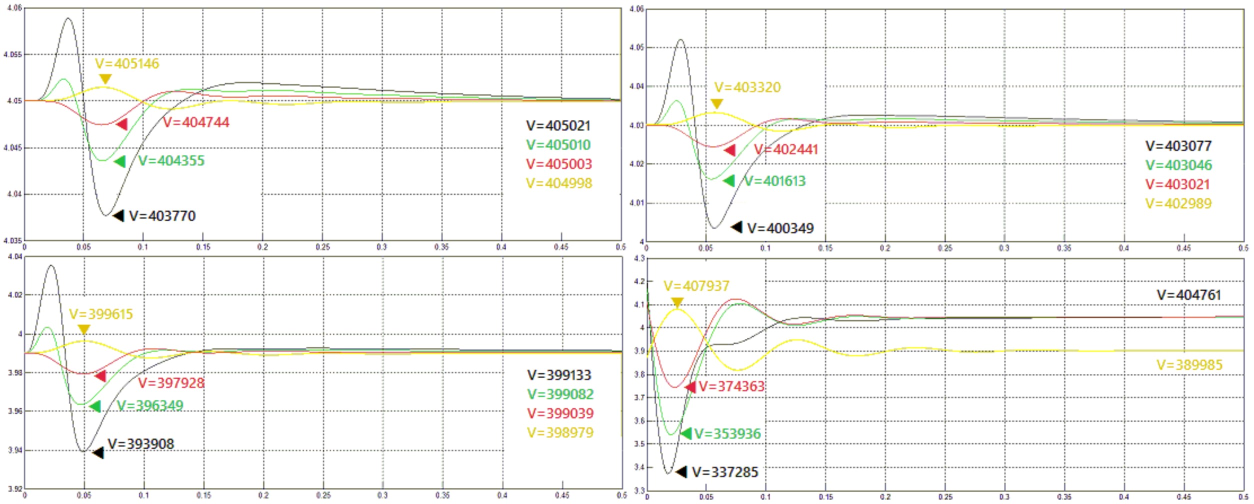


Figure 4.19: Evolution of Voltages in the first period with different references and PI control: from Node 5 to Node 8

The evolution in Figure 4.20 and 4.21, are the evolution with the reference of node 8 equal to 411000 V. In this case, all nodes start and converge into their admissibility region. As in the previous section, the blue line represent the evolution of the first period, the black represent the second period and the green the third.

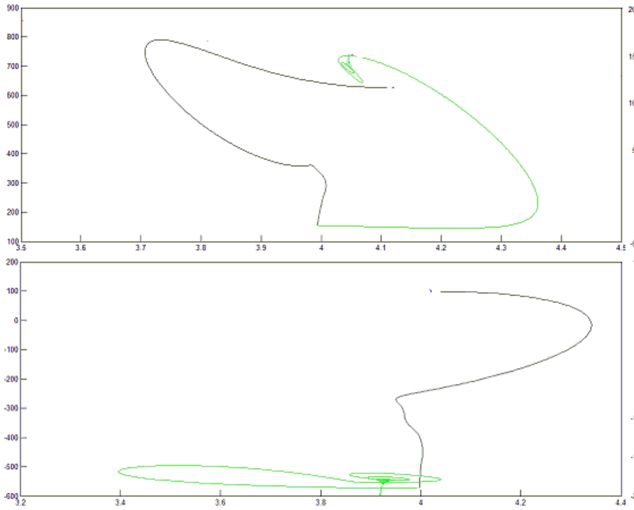


Figure 4.20: Evolution of Voltages in all periods with different references and PI control: from Node 1 to Node 4

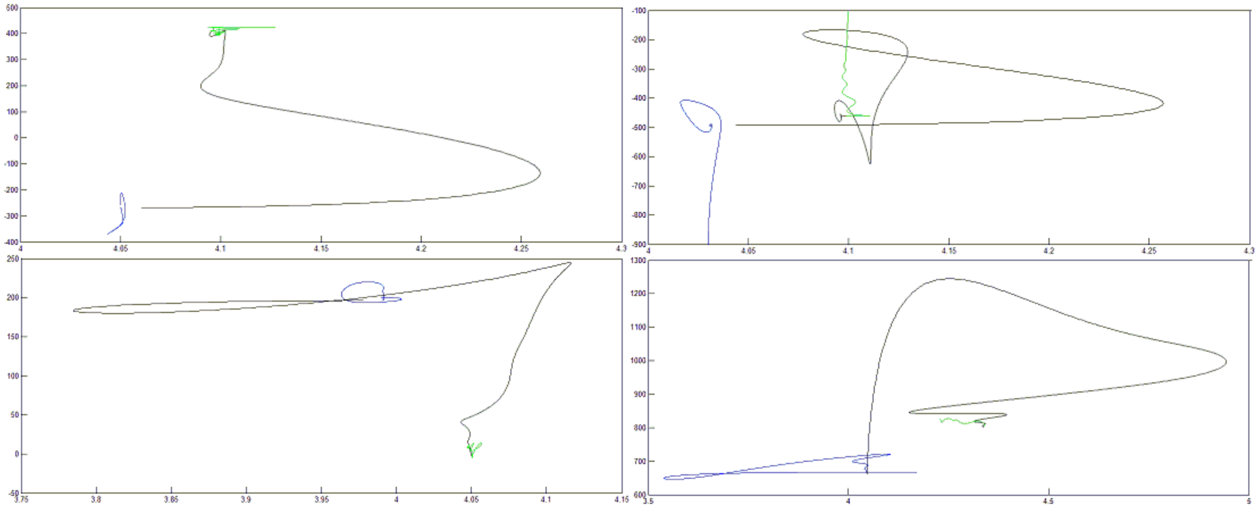


Figure 4.21: Evolution of Voltages in all periods with different references and PI control: from Node 5 to Node 8

The influence of the variation of the reference of node 8 is lower then the variation of the reference of the node 1. The pikes in the transitory in each period don't depend by the references of the node 8. Only in the nearest nodes there are some valuable variation.

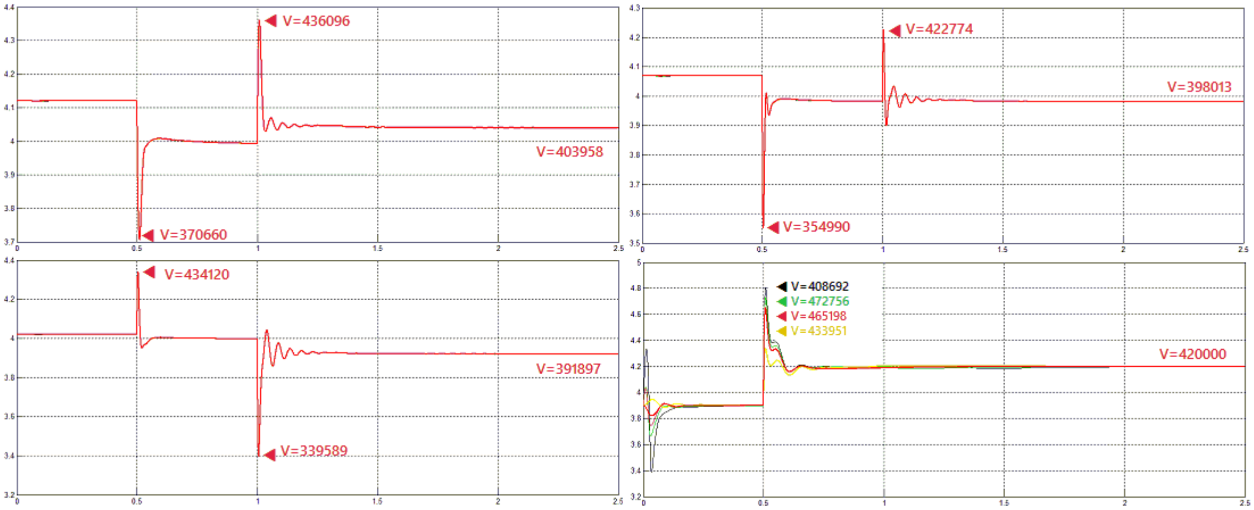


Figure 4.22: Evolution of Voltages in all periods with different references and PI control: from Node 1 to Node 4

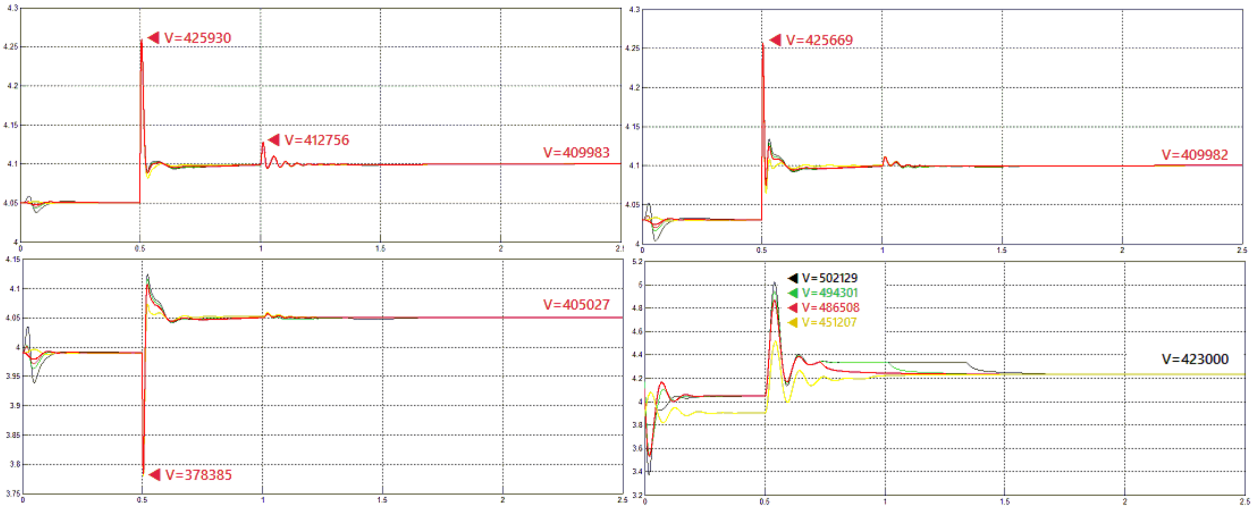


Figure 4.23: Evolution of Voltages in all periods with different references and PI control: from Node 5 to Node 8

4.2.2 Hub

4.2.2.1 Node 2

The references for the Node 2 are divided in two categories: the first are the references stay up the admissibility region; the second stay under the admissibility region. The influence on the network is different if the references belong to the first or second categories.

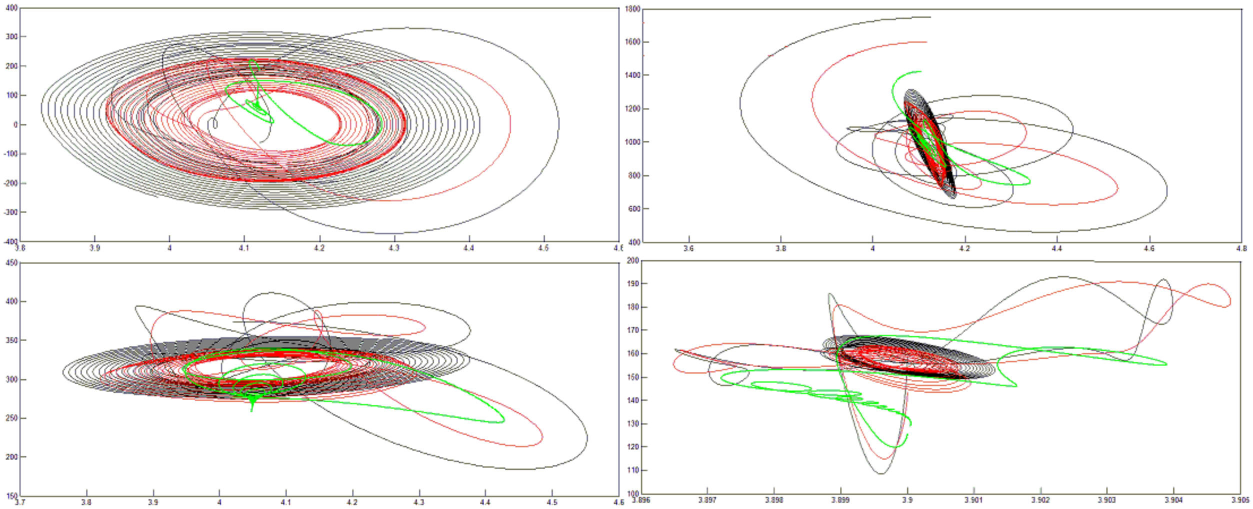


Figure 4.25: Evolution of state variables in the first period with different references and PI control: from Node 1 to Node 4

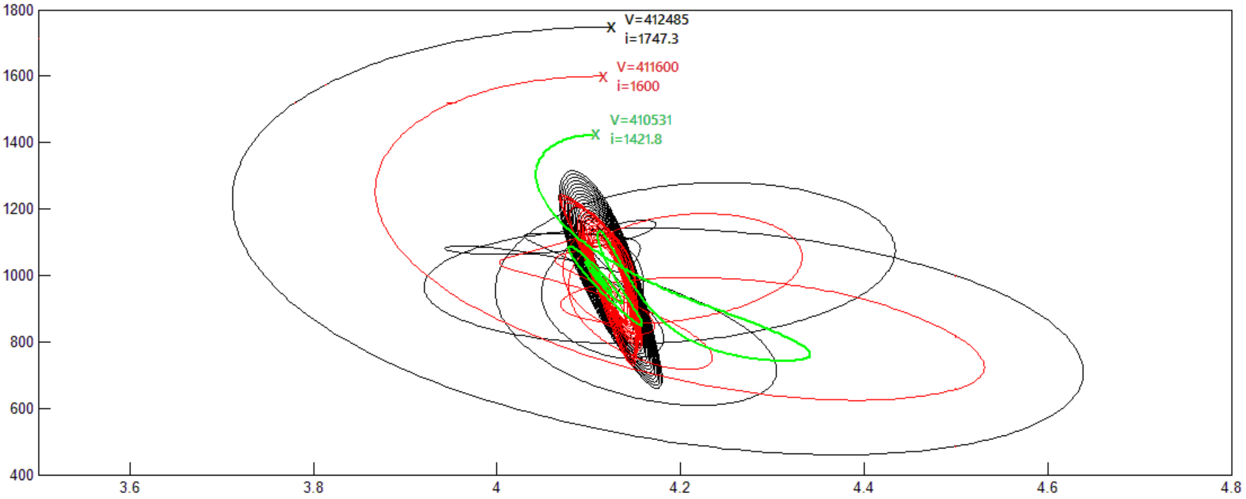


Figure 4.24: Evolution of state variables of Node 2

Closer are the nodes, higher is the influence. The nodes 1 and 3, that are directly connect with node 2, with the higher reference go out the admissibility region. Also nodes 5 and 6, that are directly connected to node 2, undergo changes The variations of far nodes, like 4, 7 and 8, are lower then the near nodes.

The voltages in the first period are very influenced by the variation of the reference of node 2. In figure 4.27 and 4.28 there are the evolution of the voltages of all nodes in the first period. In every nodes, the black lines after a little transitory have an oscillatory and divergent behavior. In this case the voltages don't converge and the amplitude of oscillation become larger. This is the worst case for the system because in the first period the nodes don't follow the references. Instead the red lines also have an oscillatory trend, but after few seconds, depending on the nodes, this behavior vanish, and converge to a value close to the references. The green lines show the best behavior because after a little transitory, converge

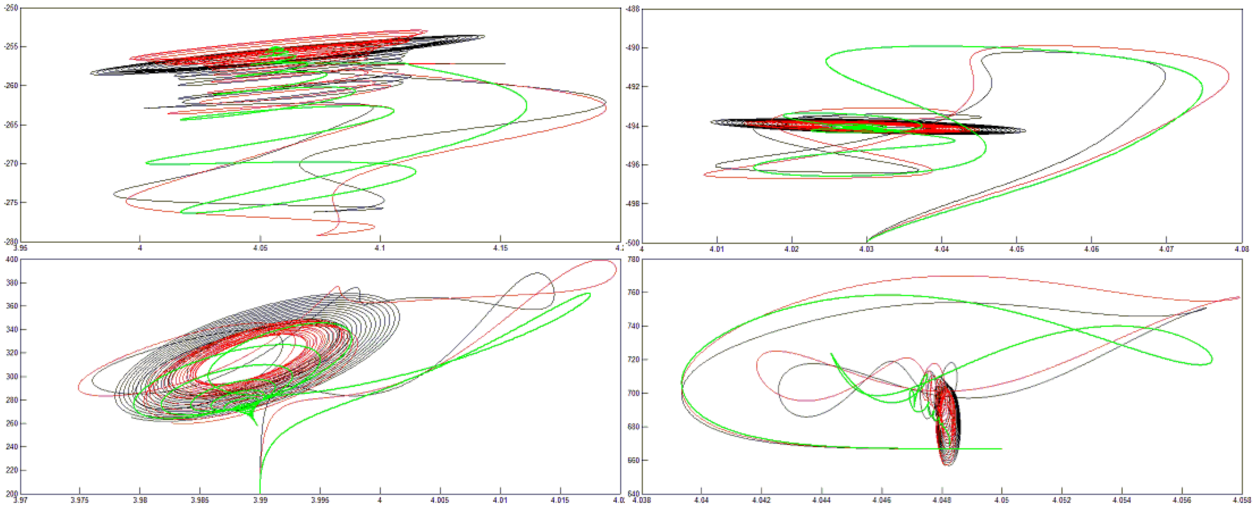


Figure 4.26: Evolution of state variables in the first period with different references and PI control: from Node 5 to Node 8

to a values equal to the references. This is the first case when the influences on the other nodes don't depend by the distance. All nodes show the same behavior.

In Figure 4.29 and 4.30, the state variables of the nodes 3, 4 and 8 during the evolution go out their admissibility region. In the other nodes, all start points and end points are into the admissibility regions.

Only the pikes in the transitory of the second period are affected by the variation of the reference of node 2. The pikes of the voltages in the third period and the values of voltages after 1.5 seconds, don't depend by the variations. All nodes follow their references.

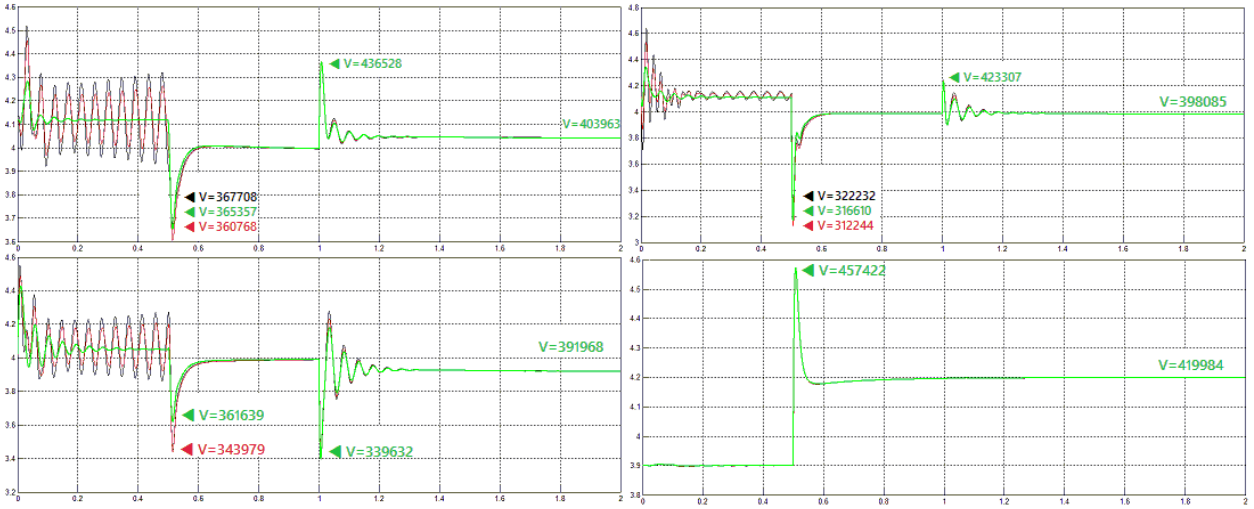


Figure 4.31: Evolution of Voltages in all periods with different references and PI control: from Node 1 to Node 4

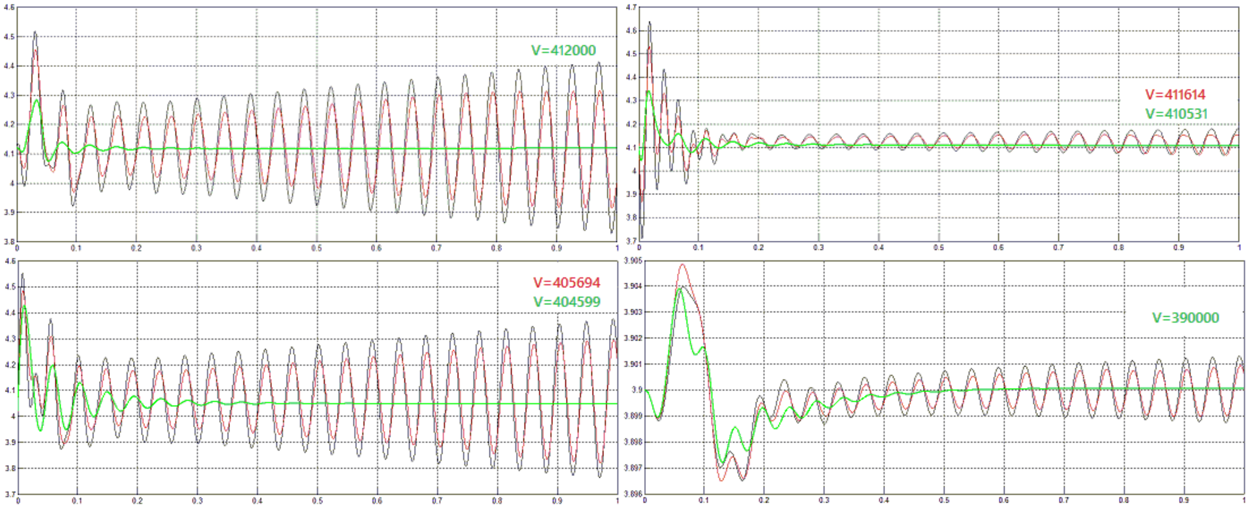


Figure 4.27: Evolution of Voltages in the first period with different references and PI control: from Node 1 to Node 4

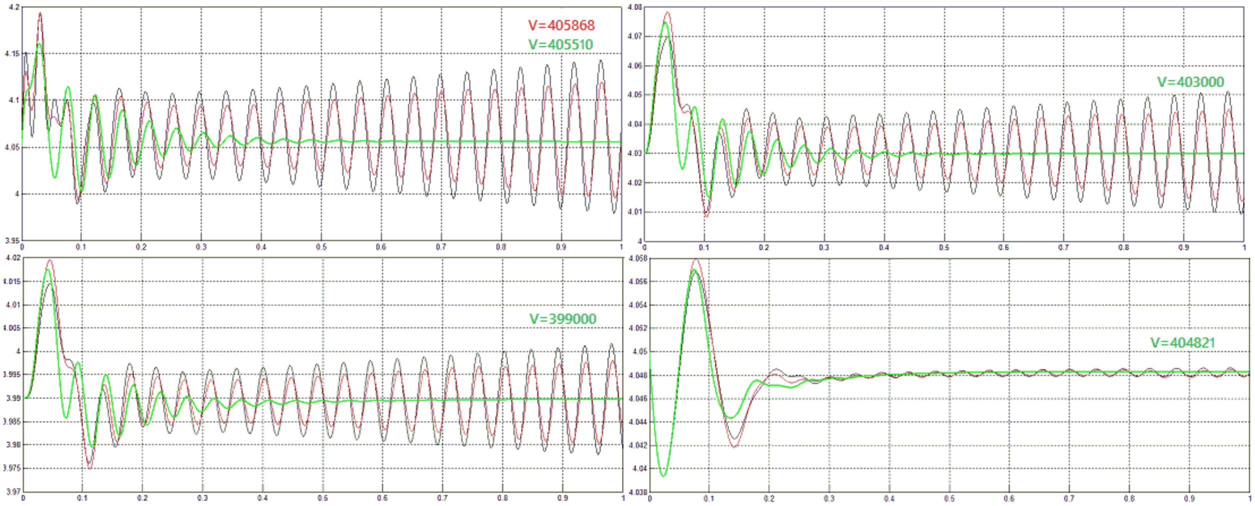


Figure 4.28: Evolution of Voltages in the first period with different references and PI control: from Node 5 to Node 8

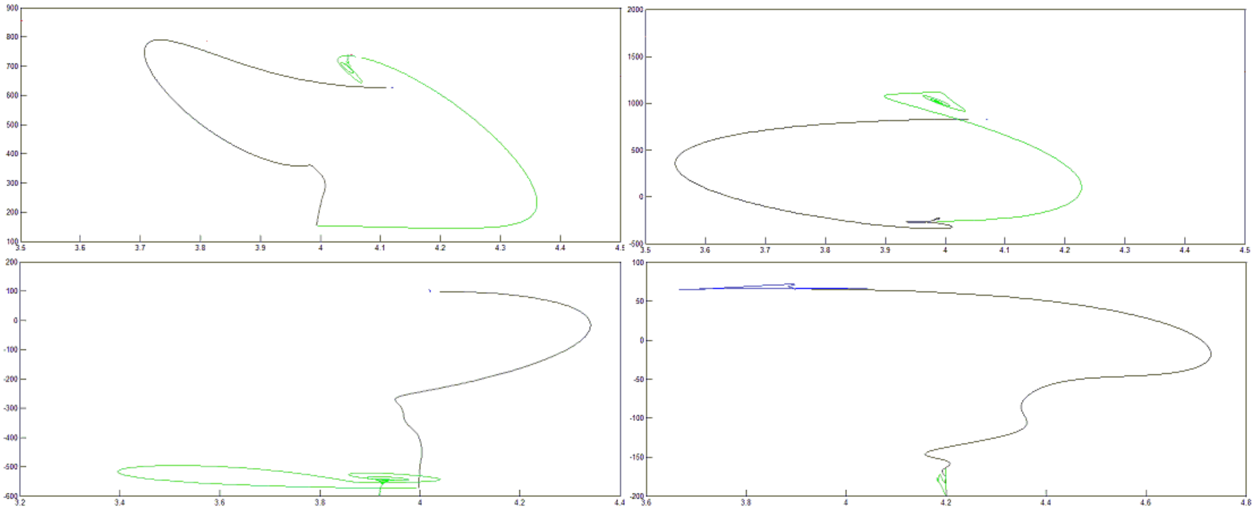


Figure 4.29: Evolution of Voltages in all periods with different references and PI control: from Node 1 to Node 4

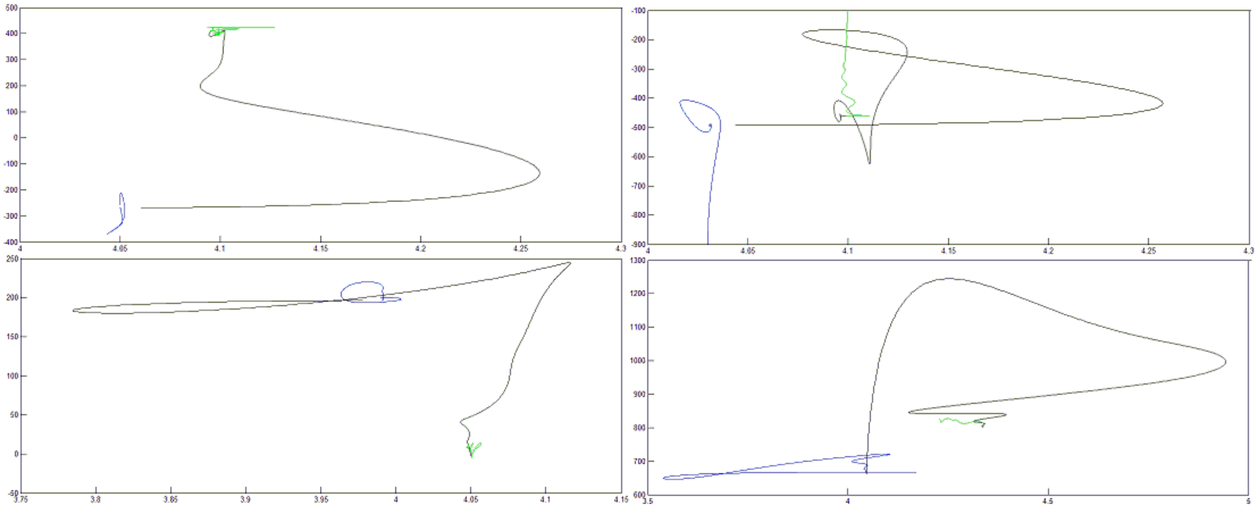


Figure 4.30: Evolution of Voltages in all periods with different references and PI control: from Node 5 to Node 8

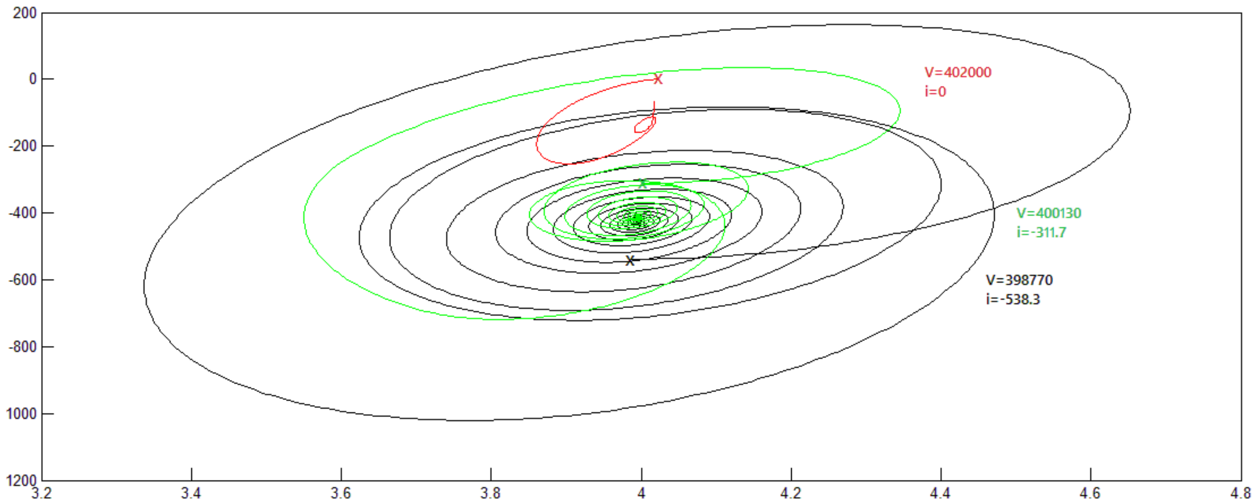


Figure 4.33: Admissibility region Node 2

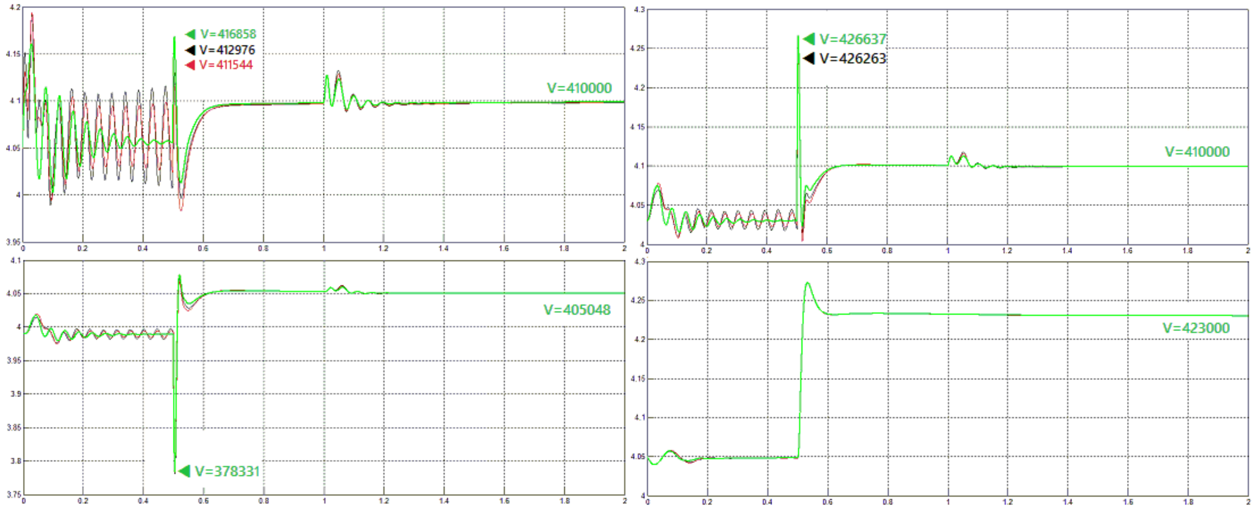


Figure 4.32: Evolution of Voltages in all periods with different references and PI control: from Node 5 to Node 8

Whit different values of the references, there are different start point for the nodes 1, 3 and 4. Also here, closer are the node, higher are the influence on the other nodes.

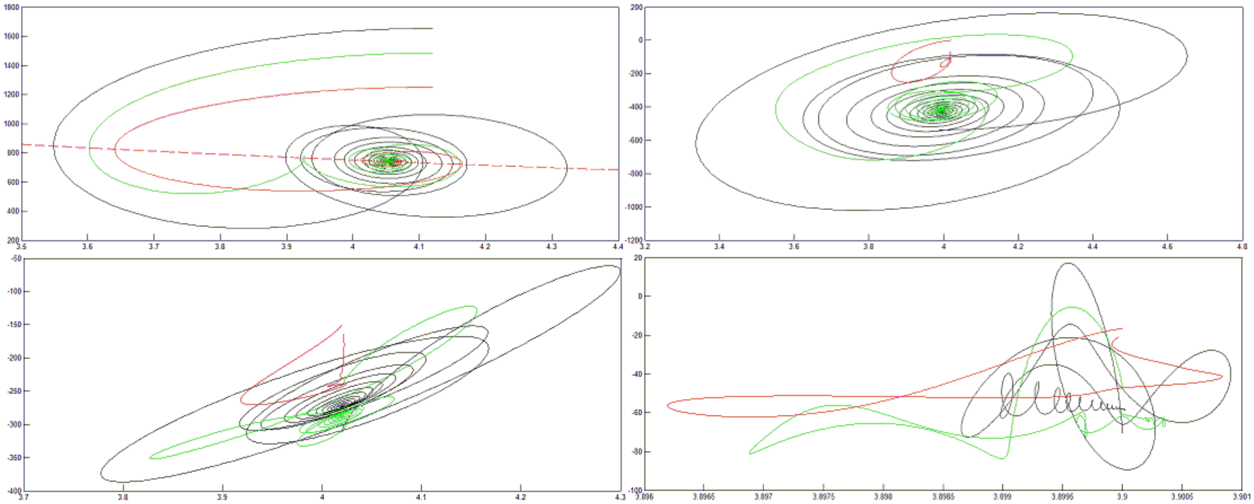


Figure 4.34: Evolution of state variables in the first period with different references and PI control: from Node 1 to Node 4

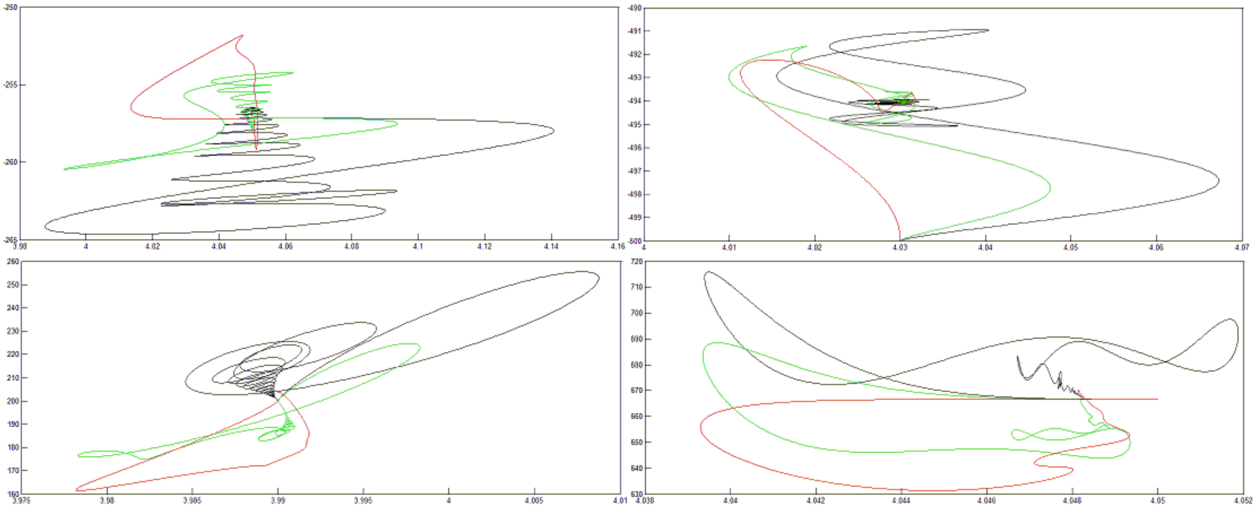


Figure 4.35: Evolution of state variables in the first period with different references and PI control: from Node 5 to Node 8

Higher are the reference, higher are the value of the pikes in the transistorizes. It's the same for the voltages at 0.5 seconds. Only the voltage of node 1 is lower then the reference.

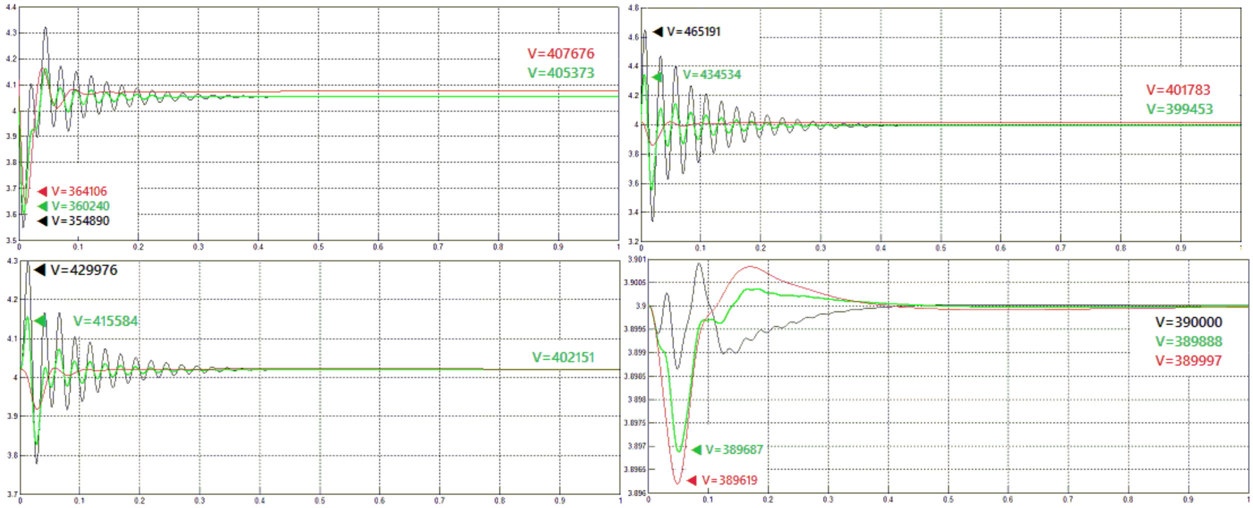


Figure 4.36: Evolution of Voltages in the first period with different references and PI control: from Node 1 to Node 4

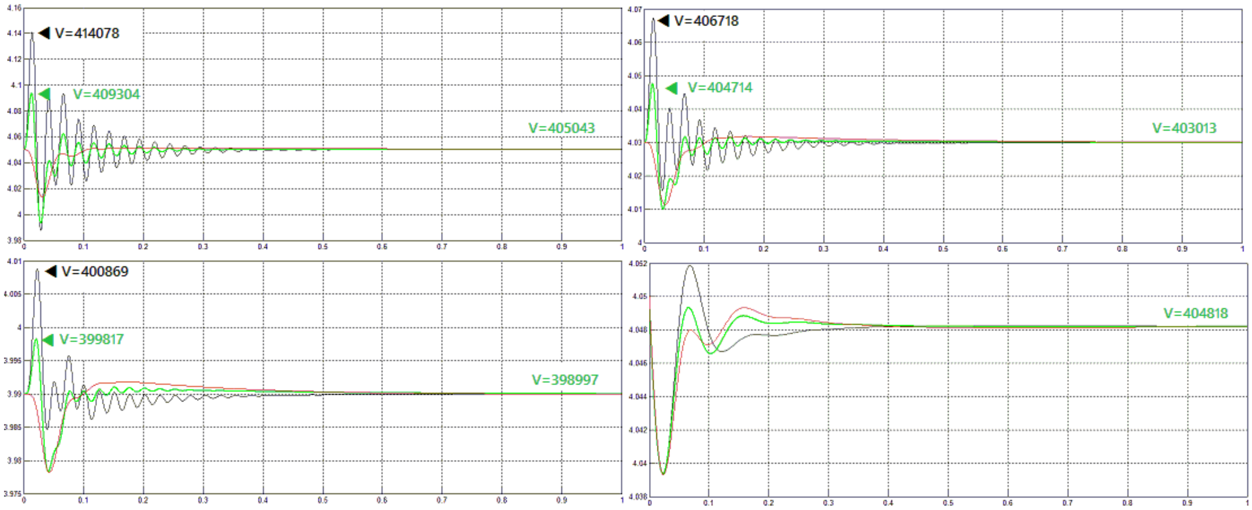


Figure 4.37: Evolution of Voltages in the first period with different references and PI control: from Node 5 to Node 8

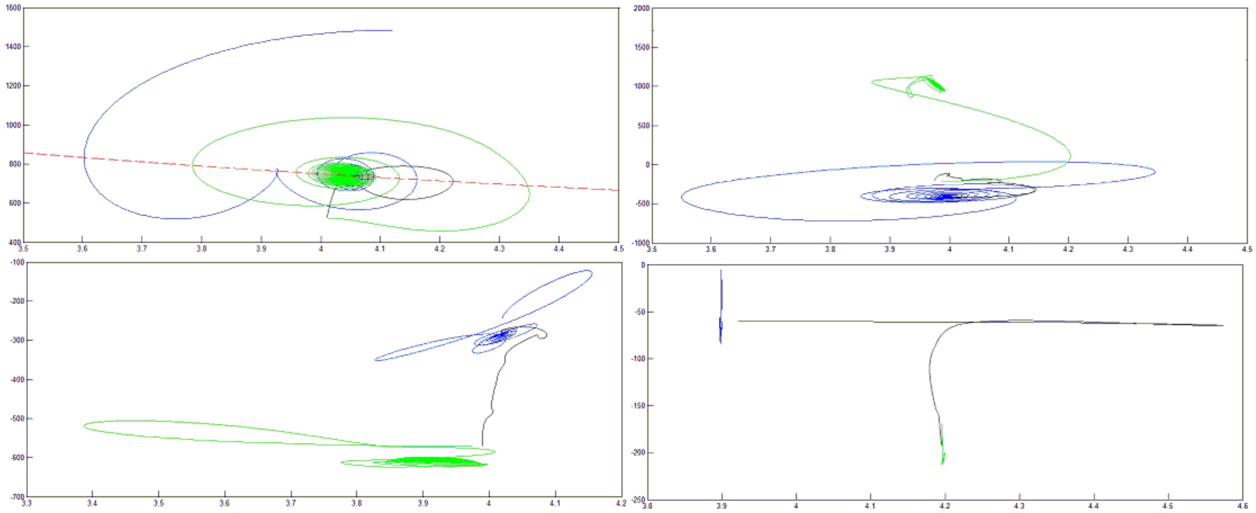


Figure 4.38: Evolution of Voltages in all periods with different references and PI control: from Node 1 to Node 4

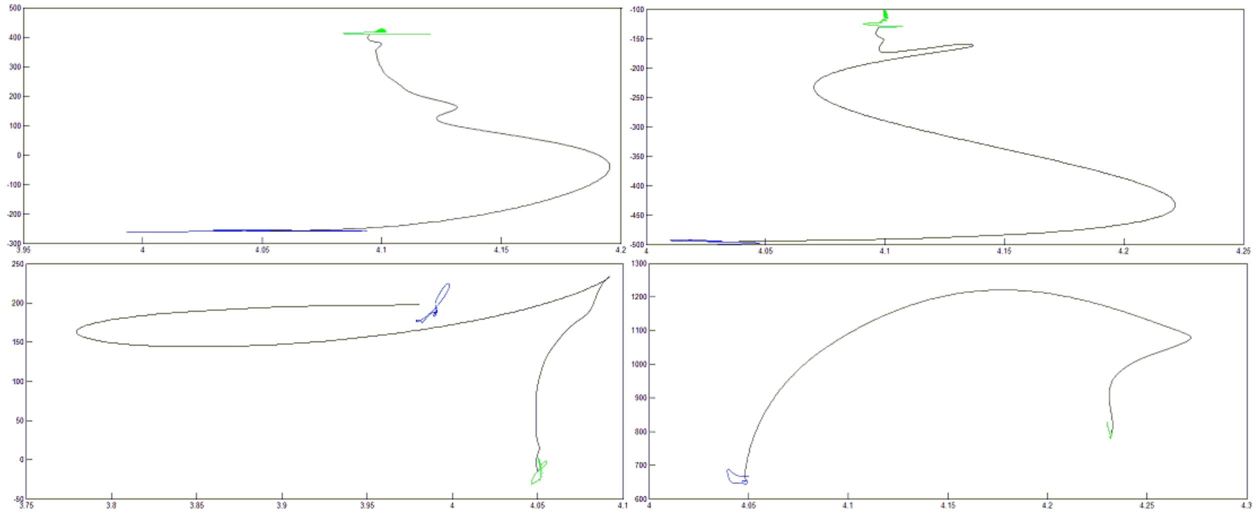


Figure 4.39: Evolution of Voltages in all periods with different references and PI control: from Node 5 to Node 8

In the third period there are a lot of oscillations in the transitories of the near nodes. The far nodes don't are affected by the variation of the reference of node 2.

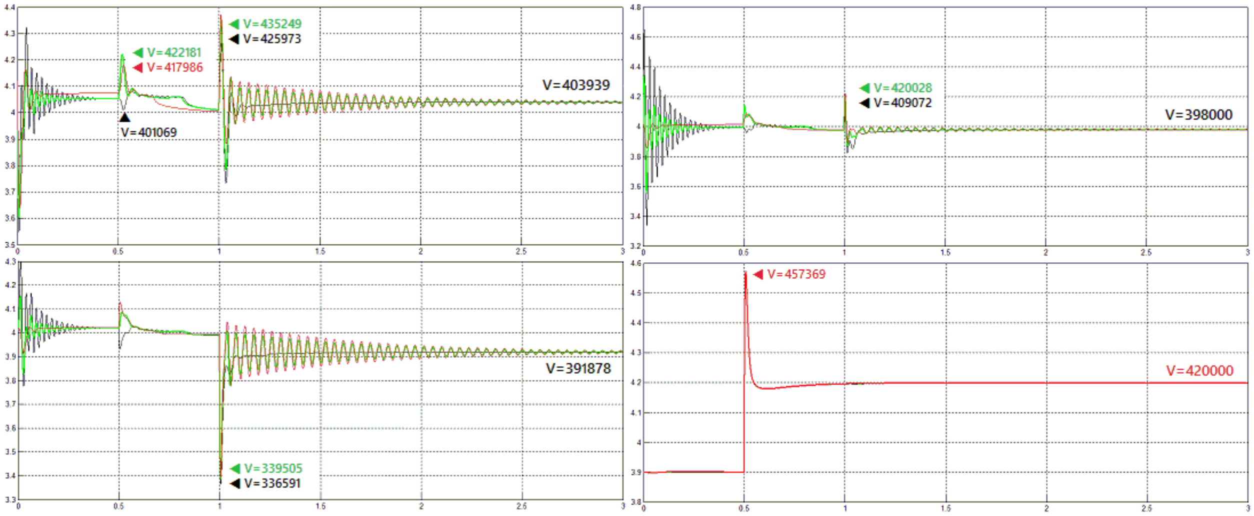


Figure 4.40: Evolution of Voltages in all periods with different references and PI control: from Node 1 to Node 4

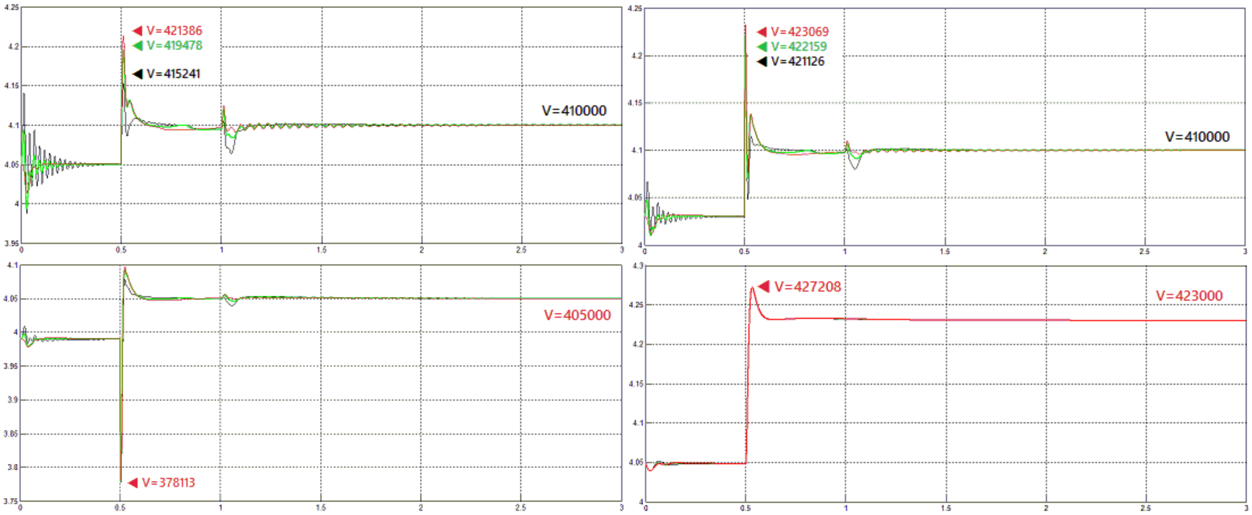


Figure 4.41: Evolution of Voltages in all periods with different references and PI control: from Node 5 to Node 8

4.3 Comparison between P and Pi control

This chapter show the difference between the application of P control and PI control. There are different values of the proportional control. The first value is equal to 0.75. The other values are equal to 0.041 and 0.0189. These values are represent different condition for the system. When the proportional control has value lower then 0.041, the nodes 1, 2 and 3 lost their oscillation trend in the third period. The control action with proportional control equal to 0.0189 is the value obtained to the application the Ziegler-Nichols rules. In the same way, it's possible to obtain the value for the PI control. In general the application of the P control with different values has the effect . The application of PI control leads

4.3.1 Node pour of connection

4.3.1.1 Node 1

In Figure 4.42 there are different evolution of the voltages of node 1 whit different values of the P control and PI control. In all situations, higher are the references of the Node, lower are the value of voltages at 0.5 seconds. In facts, in every condition, the red lines, who represent the evolution of the voltage when the reference is equal to 413000, are on top then the other lines. Hence, the variations of the references keep this behavior. When the value of the action control changes, there are variation in the transitory and in the values of the voltages at 0.5 seconds. For example, lower is the value of the control action, higher are the pikes in the transitories of each periods. Whit PI control, the pikes are lower then the P control with value equal to 0.0189 but higher then the P control with value equal to 0.041. For the values of the voltages at 0.5 second, the variation of the P control has a great influence. Lower is the value of the P control, lower are the values of the voltages at 0.5 seconds. For this reason, the voltages with a low control action, assume values lower then the references at 0.5 seconds. This behavior isn't present with the PI control. All voltages follow the references of the first period. In the second period, the variation of control leads only variations in the pike of the transitories. Anyway, in every control, the voltages follow the references of second period. In the third period there are different evolution. The oscillatory trend is present with proportional control. Lower is the value of control, higher are the amplitude and frequency of the oscillation. With value of control equal to 0.0189 and PI control, the oscillatory trends vanishes. In the case of the PI control, the variation of the references influence the oscillation of the system. Higher are the references, higher are the start amplitude and longer is the transitory. The PI control is the only case when the change of reference leads some variation in the behavior of the voltage in the third period. Howe where, the PI control is more precise the the P control.

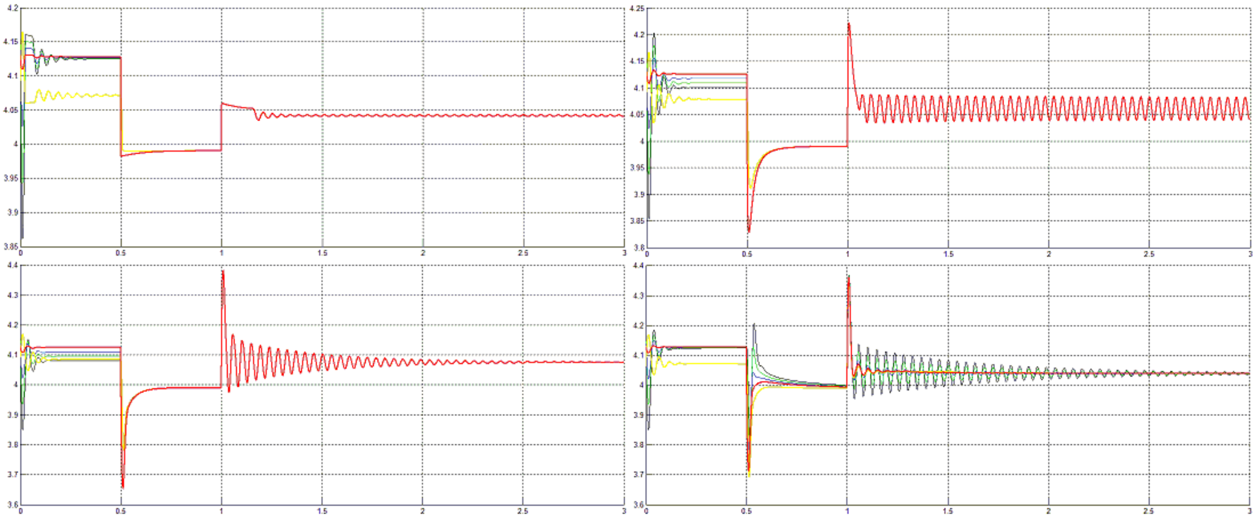


Figure 4.42: Voltages of node 1 with different action control

The Figure 4.43 show the differences in the Node 2. This is directly connected with Node 1. For this reason it is the node which suffers the most of the reference variations. It shows the same behaviors of the Node 1.

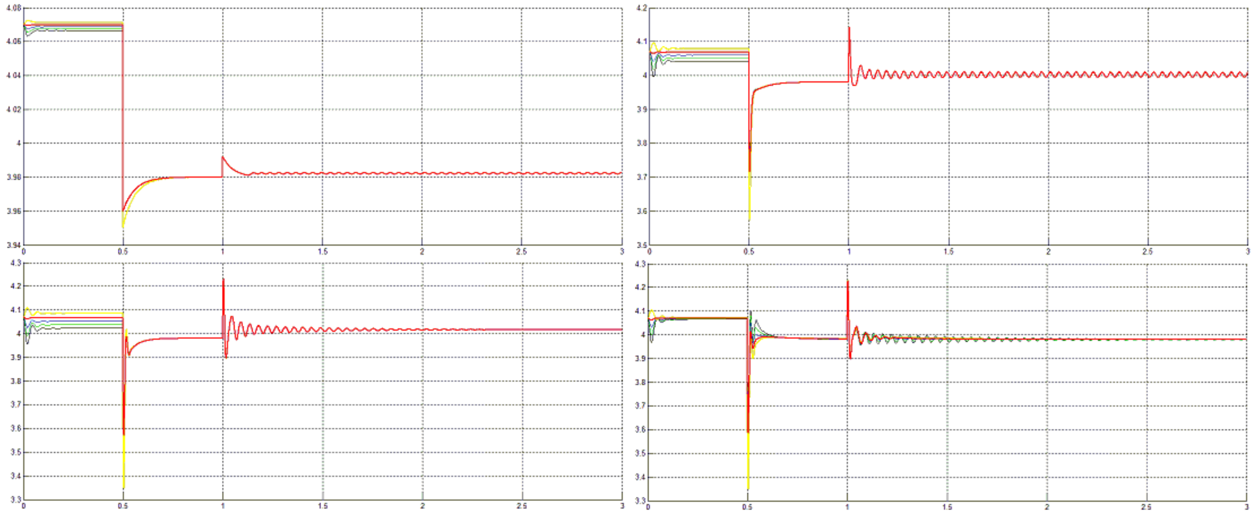


Figure 4.43: Voltages of node 2 with different action control

The evolution of Node 3, Figure 4.44, present a similar trend of node 1 and 2, but lower is the P control, lower are the amplitude and frequency in the third period. This node isn't directly connected to the Node 1. For this reason the changes of the references of Node 1 are lower then the node 2. In facts, the variations of the voltages in the first period, are lower then the Node 2.

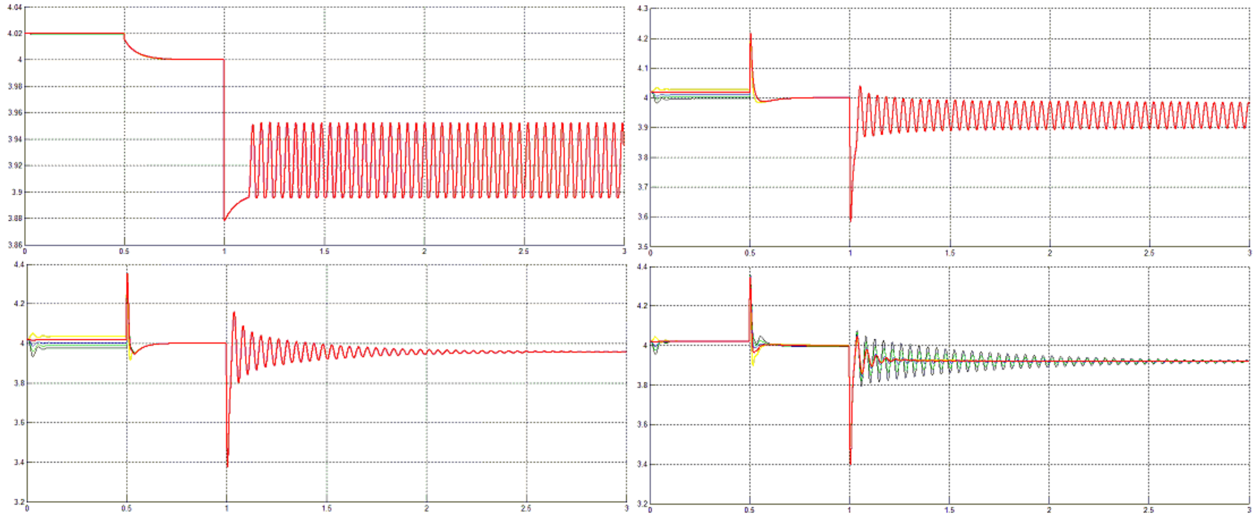


Figure 4.44: Voltages of node 3 with different action control

The Node 8 is the further node. There are variations only in the pikes of the transitories of the second period. In the other periods, the voltages follow the references. In conclusion, the far nodes don't are affected by the variation of the references of Node 1.

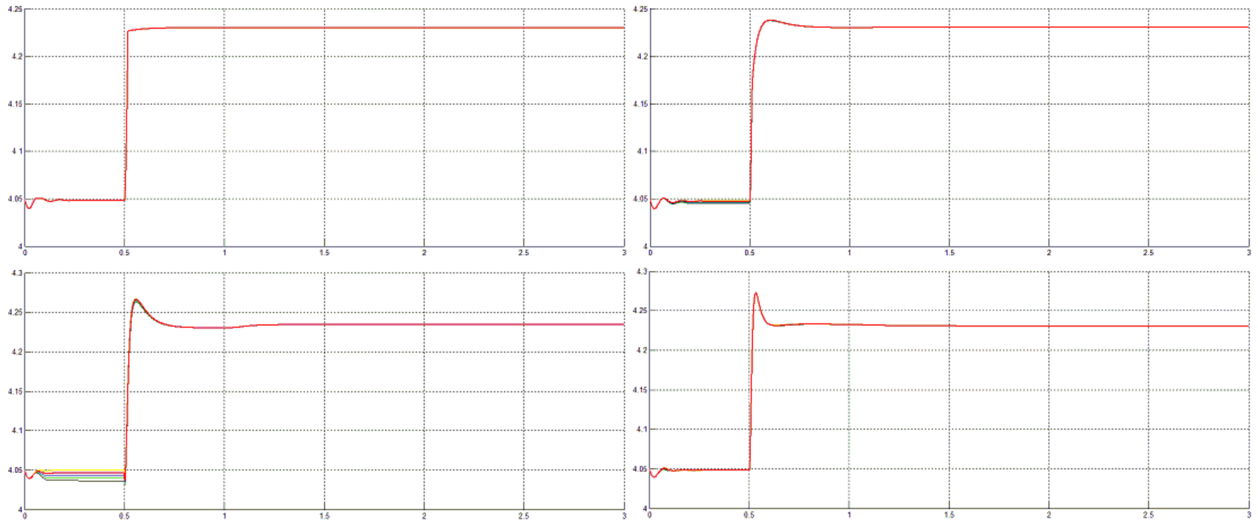


Figure 4.45: Voltages of node 8 with different action control

4.3.1.2 Node 8

Node 8 is a node pour of connection and it's far from the node with more connection. The value of the references are equal to: 423000 V (black lines); 417000 V (green lines); 411000 V (red lines); 387000 V (yellow lines). The application of different kind of controls lead different reactions, on the system, in the different periods. In the first period, where there are the changes of the references of node 8, the influence of the variation of the references are higher then the other periods. In facts, lower is the P control, lower are the value of the voltages at 0.5 seconds. In this way with P control, the voltages don't follow the references of the first period. With PI control the voltages follow the references. In the other periods, lower are the P control, higher are the pikes. In this case, the variations of the references don't involve some change in the evolution of the voltages. Then, the P control follow the references of the second and third period. This behavior isn't the same with the PI control. The variations of the references lead some change in the variation of the voltage at 1 and 1.5 seconds. Furthermore, the pike in the transitory of the second period give the voltage out of the admissibility region. This doesn't happen with P control.

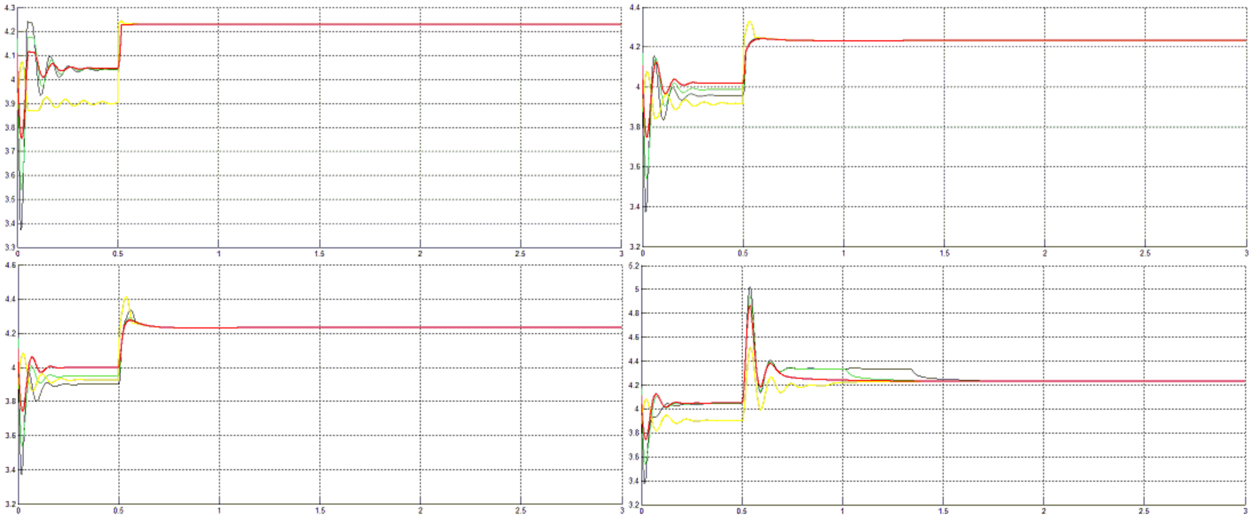


Figure 4.46: Voltages of node 8 with different action control

The Figure 4.47 shows the evolution of the voltages of node 4 with different control actions. Node 4 is directly connected with Node 8. As usually, lower are the value of the P control, lower are the values of the voltages in the first period. The changes of the references lead some changes in the pike of the transitories of the second period. At the end, all the voltages follow the references of the other periods. In the case of PI control, the reference of the first period is followed by the voltages independently by the values of the references.

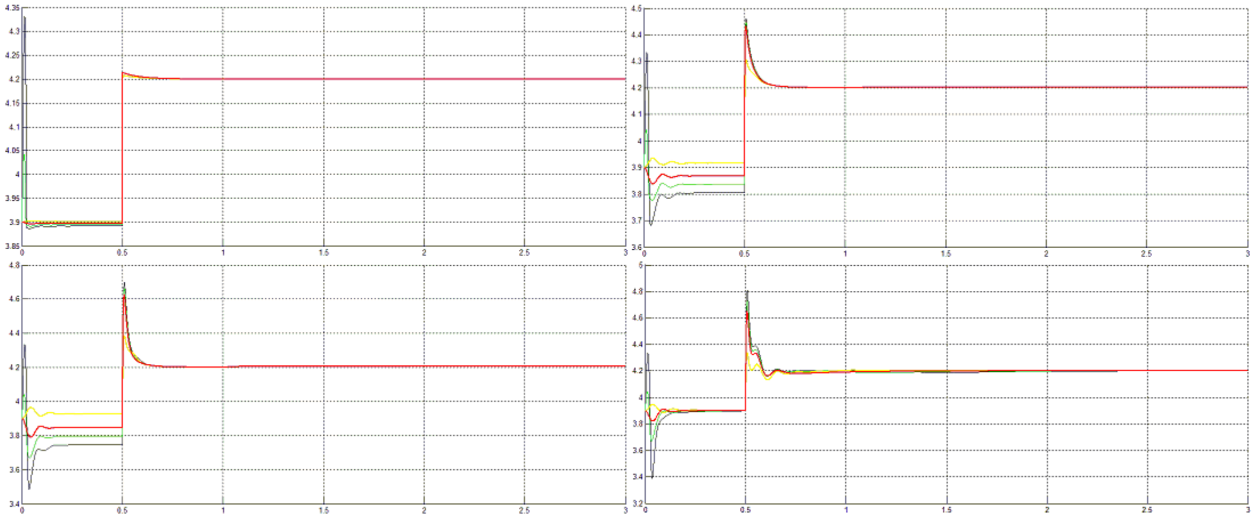


Figure 4.47: Voltages of node 4 with different action control

The Node 1 is the further for Node 8. There aren't valuable variation in the voltages, but the application of different control leads different behavior. The pikes in the second and third transitories are higher than the pikes in the same periods with the P control. Furthermore, with PI control there aren't any kind of oscillation in the voltages. With the P control, only with a value lower than 0.041, the voltages in the third period converge to a value near the reference on the same period.

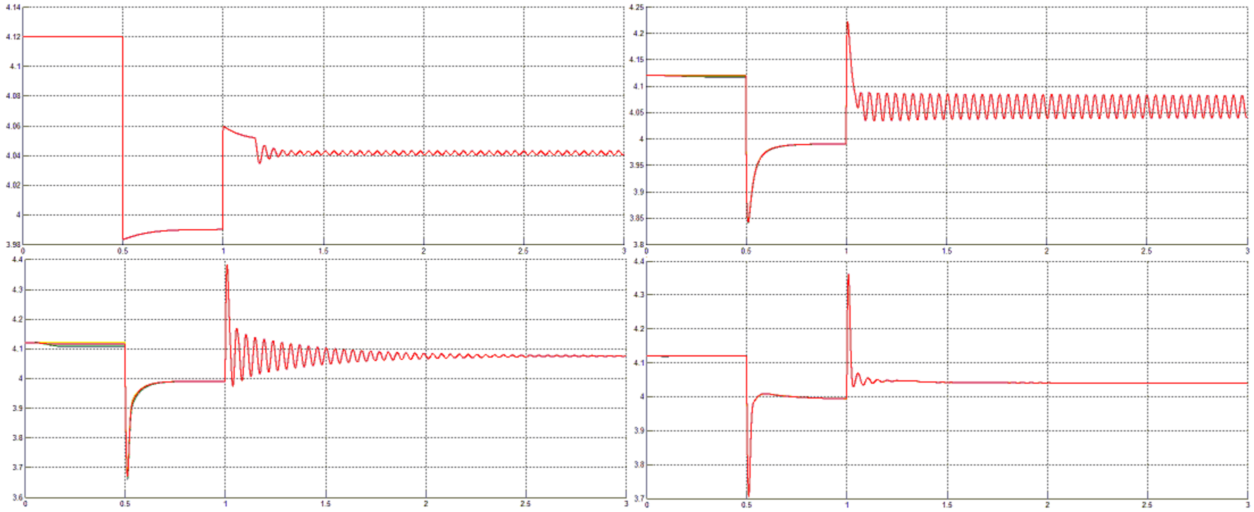


Figure 4.48: Voltages of node 3 with different action control

4.3.2 Hub

4.3.2.1 Node 2

Node 2 is an hub for the network. Figure 4.49 shows the evolution of the voltages Also in this case, with P control is present an oscillatory trend in the third period. This behavior is present only when the value of action control is higher than 0.041. When the value is lower than 0.041, the oscillation vanishes. This is not the only difference.When the value of the proportional control is equal to 0.0189, the value of the voltage at 1.5 sec, is higher than the reference in the same period. With PI control, this doesn't happen. In facts, the voltage in the third period follows the reference of the same period. For this reason, the PI control is better than P control to follow the references. The problem of PI control are the pike in the first period and influence of the references for the evolution of voltages. In facts, the pikes of the first and second periods are out of the admissibility region and higher are the reference, higher the value of the voltage.

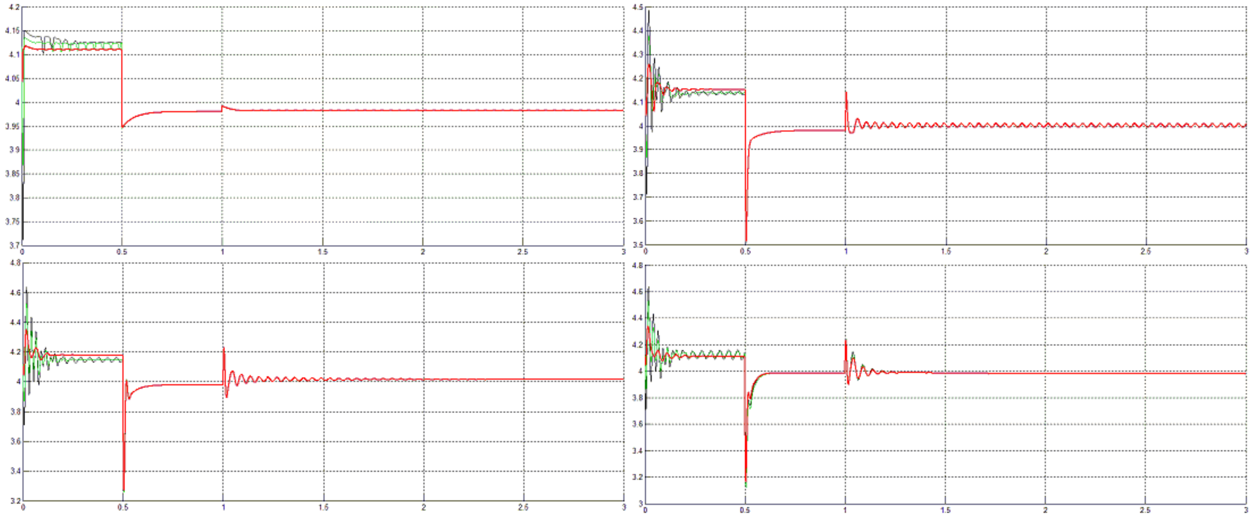


Figure 4.49: Voltages of node 2 with different action control

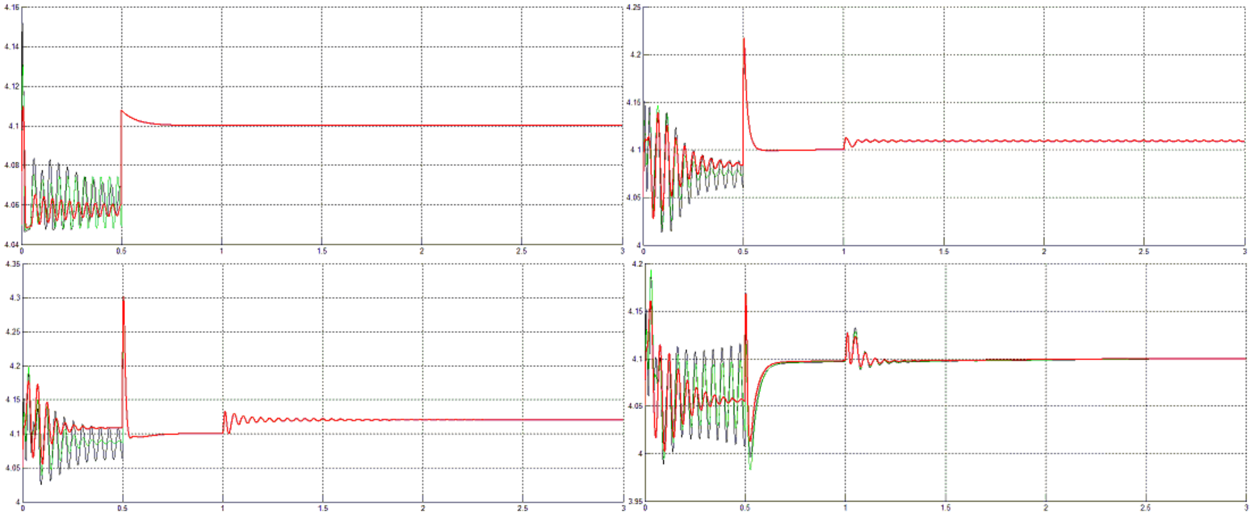


Figure 4.50: Voltages of node 5 with different action control

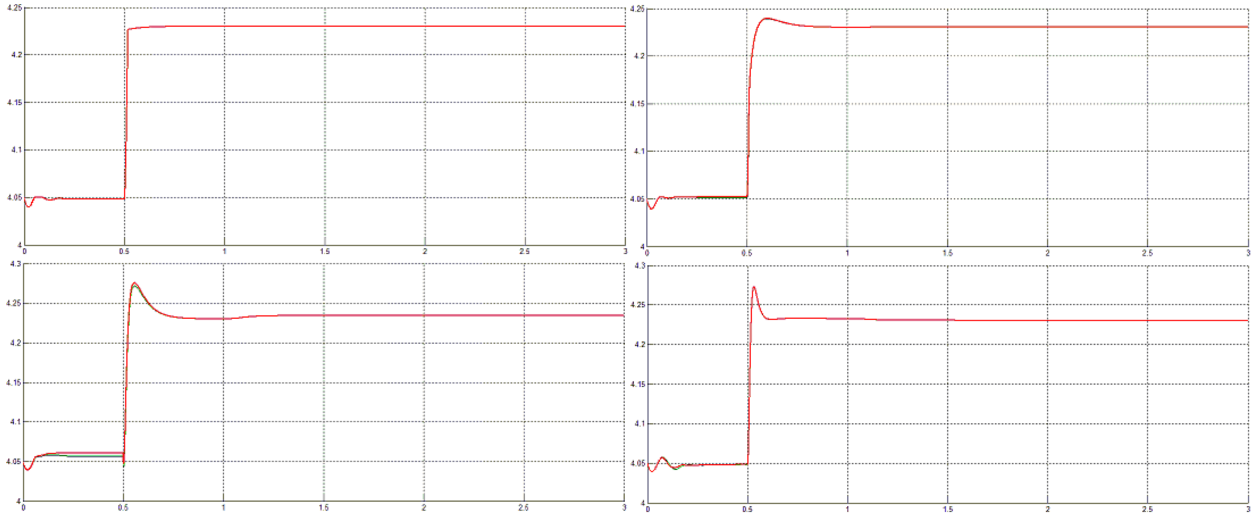


Figure 4.51: Voltages of node 8 with different action control

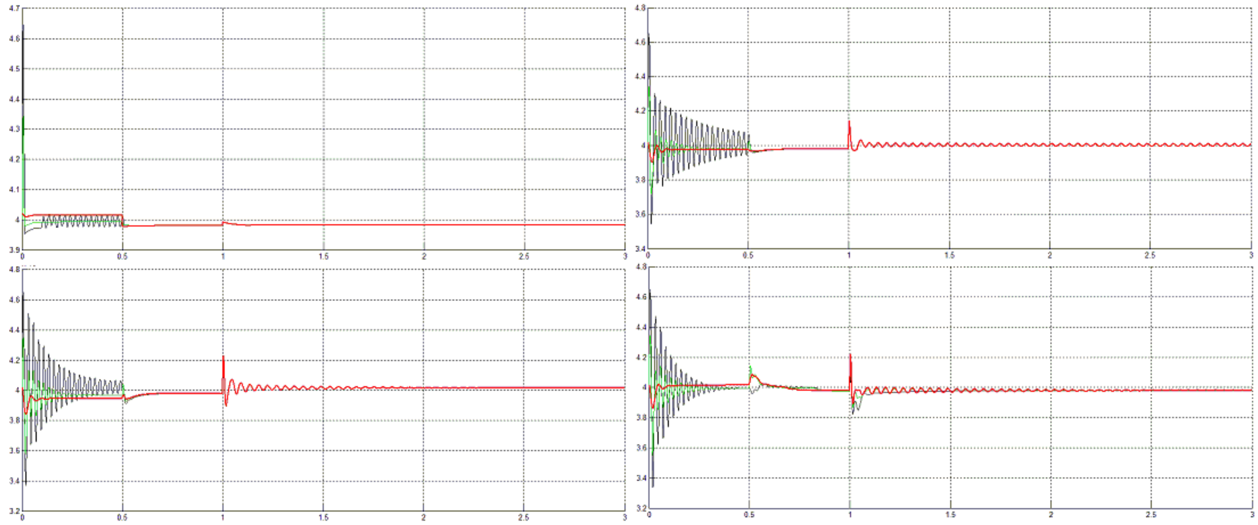


Figure 4.52: Voltages of node 2 with different action control

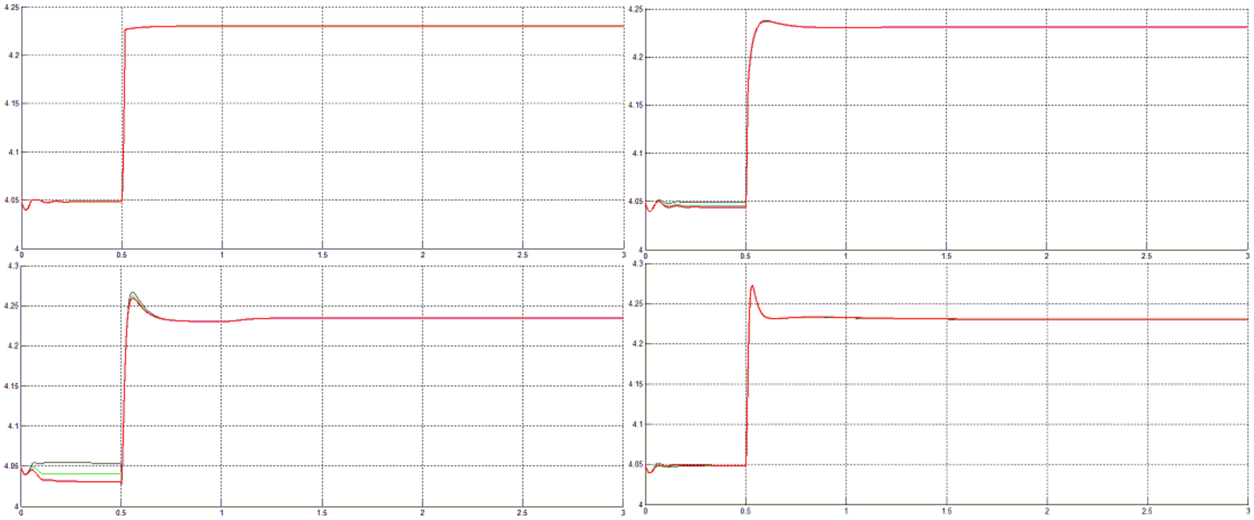


Figure 4.53: Voltages of node 8 with different action control

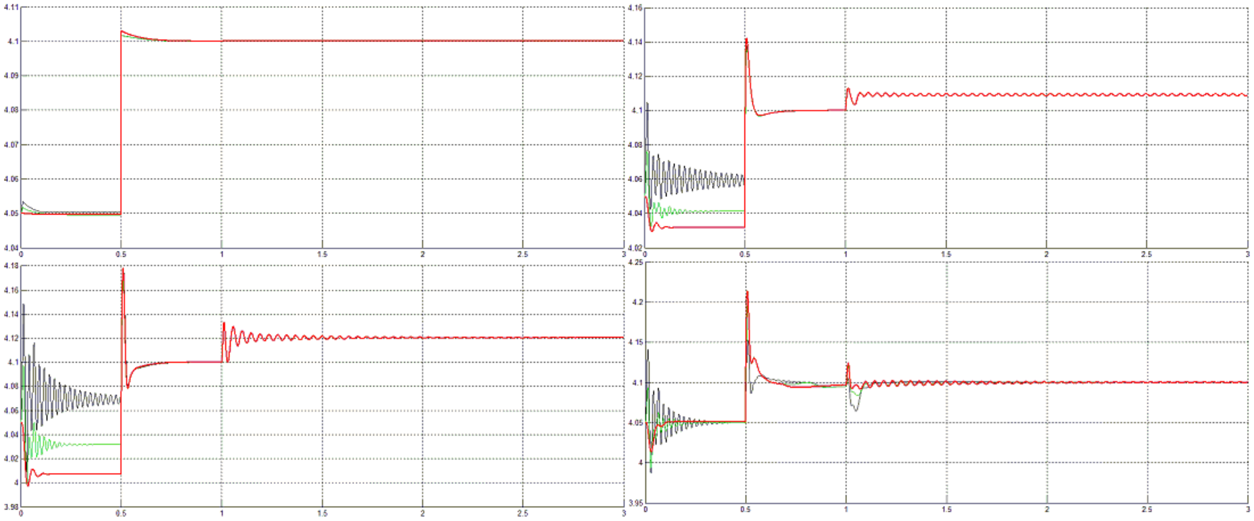


Figure 4.54: Voltages of node 5 with different action control

4.4 Effects of change of the P and I gains

With a control PI, the most important problem is that the voltages go out of the region admissibility of voltage. The strength of this kind of control are that the reference of each nodes are more precises. The Figure 4.55 show the region of the value of the gains of the control where it's possible to obtain various behavior of the voltage. The blue line represent the values of K and Ki whereby the voltages of the system obteined an oscillatory behavior after 1.5 seconds. In the right side of the blue line, all voltages of the nodes of the network, obtained an increasing oscillatory trend, and after 1.5 seconds each nodes lost their references.This region is called d When the value of K and Ki are under the blue line, the Nodes converge to reference. The black line represent the first value of the proportional gain

K where the nodes 3 and 4 have their voltage into the admissibility voltage region. If the value of proportional gain is under that value, the voltages are out of the admissibility region. The green line represent the value of the Integrator gain that vanish the oscillatory in the transitory. In the left side of the green line, all nodes have a long oscillating transitory and lesser is the value of Ki longer are the transitory. The red line represent the best condition to work. In the right side of that line, the transitory increase and there are an oscillatory trend. In this way, the best condition to work are in the Zone A, but the transitory is more long then the Zone B, where the transitory is more fast, but some node have their voltage out of the admissibility region.

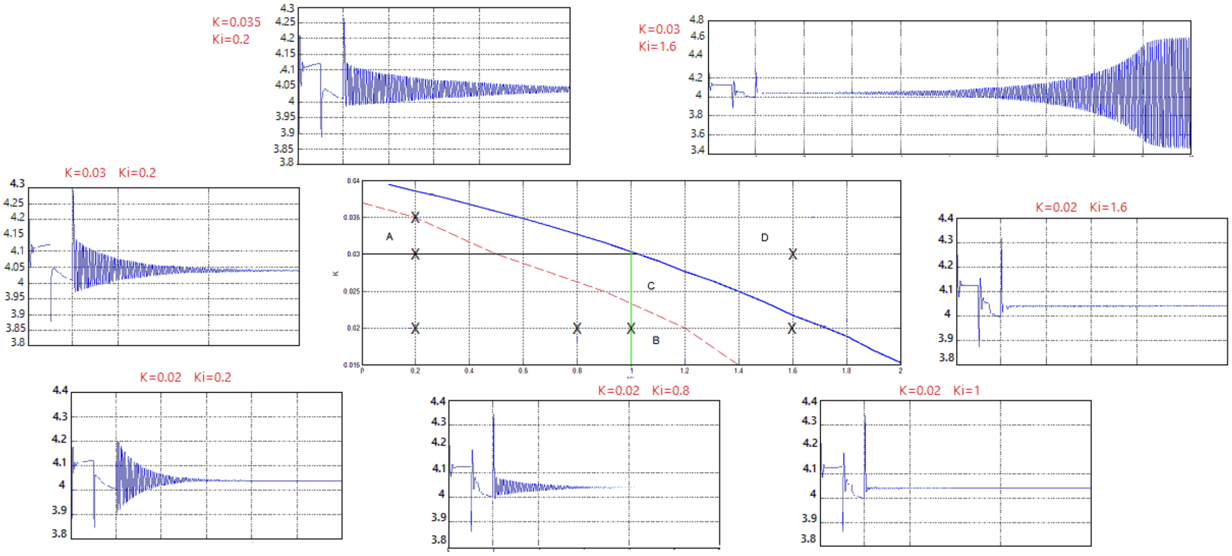


Figure 4.55: Evolution of system when Ki and K change

The Figure 4.56 shows how the system evolve when the value of the gains of the control are equal to K=0.03 and Ki=0.5.

This is an example when the initial condition of Node 1 is out of the admissibility region. The transitory are less emphatic but are more slow. In this way is possible to hold the voltages into the admissibility region.

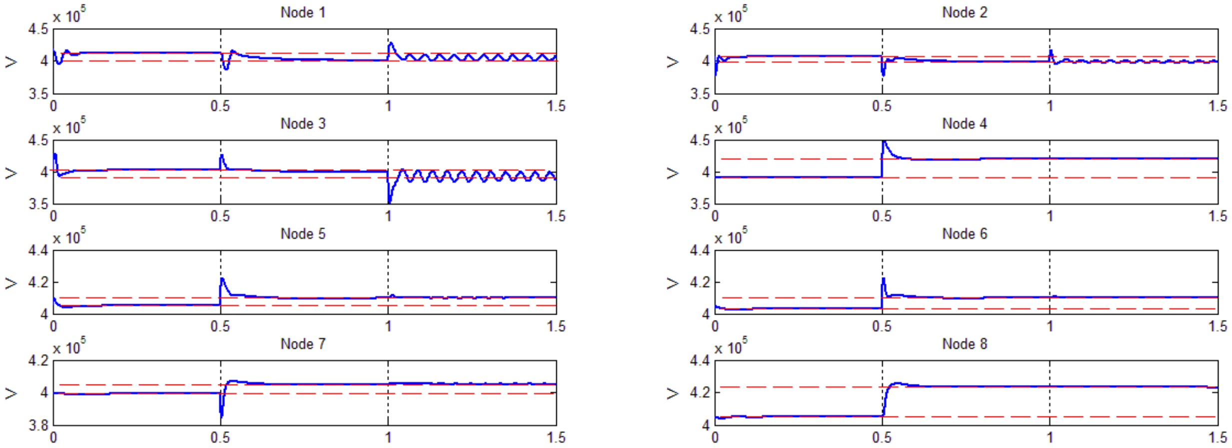


Figure 4.56: Voltages of each Nodes when change the reference of Node 1 with K=0.03 and Ki=0.5

The Figure 4.57, 4.58, 4.59, are an example of application of PI control when the value of proportional gain is fixed, K=0.015, and the value of integral gain, Ki, is variable. When the value of Ki increase, the transitory become more slow, but reduce their amplitude, until Ki=1, where the transitory after 1.5 seconds lost the oscillatory trend. The transitory when the value of Ki is equal to Ki=1.2, is more fast, but when the value of Ki is equal to Ki=1.4, the transitory become more slow and this trend is more accentuated then the value of Ki increase. This condition is because the system is near the blue line and in this way, the system is close to the oscillatory increasing trend.

"voltaggi/voltaggio1 K=0,015 Ki=variabile 1".png

Figure 4.57: Voltage of Node 1 when K=0.015 and Ki is variable

`"Nuova cartella/voltaggio1 K=0,015 Ki=variabile 2".png`

Figure 4.58: Voltage of Node 1 when K=0.015 and Ki is variable

`"Nuova cartella/voltaggio1 K=0,015 Ki=variabile 3".png`

Figure 4.59: Voltage of Node 1 when K=0.015 and Ki is variable

These Figures, show the trend of Node 1, when the value of K is constant and equal to K=0.02 and the value of Ki is variable. This network present an initial reference of Node 1 out of the region of admissibility. The behavior is the same of the Figure 4.57, 4.58, 4.59. In facts, the transitory, when the Ki increase, become more fast and after Ki=1 vanish the oscillation, but after Ki=1.2, the transitory worsen.

`"Nuova cartella/voltaggio1 K=0,02 Ki=variabile 1".png`

Figure 4.60: Voltage of Node 1 when K=0.02 and Ki is variable

"Nuova cartella/voltaggio1 K=0,02 Ki=variabile 2".png

Figure 4.61: Voltage of Node 1 when K=0.02 and Ki is variable

Chapter 5

Conclusions

In the thesis are analyzed different application of control: P control with different values of the proportional gain; PI control. In the first case, are evaluated 3 different values: 0.75, 0.041 and 0.0189.

- P=0.75: This is the value of the proportional control of [14]. Generally, further are the node, lower are the influence of the variation of the intial condition. These changes involve different evolution of the variables state only in the first period; the other periods don't depend by the initial condition. For this reason the voltages of nodes 1, 2 and 3, always have an oscillatory trend in the third period. Higher is the value of the inital condition, closer to the reference of the first period is the voltage. Also if node 1 and node 8 are both nodes with poor connection, the influence of node 1 is higher than the node 8, becouse the node 1 is directly connected to the Hub. The variation in node 2 influence all the nodes of the network.

- P=0.041: In this studied case, the oscillatory trend in the third period is always present, but the pikes of the voltages in the transitories of the periods are higher than the pikes with the proportional gain equal to 0.75. With this control, the influence of the variation of the nodes are higher than the previous case. In facts the variation in the node with poor connection, involve changes also in the far nodes. Furthermore, the voltages of the nodes don't reach the their references.

- P=0.0189: The lowest value of control leads a vanish of the voltage's oscillatory trend in the third period, but in few case, the voltages go out of the admissibility region. The influence of the variation of the initial condition are such that all nodes don't reach their references. This sittuation is the worst in all of studied case.

- PI control: This represent the better control action than the various values of the P control. The voltages in the period don't have oscillation and all voltages follow thei references. In some case, such as Node 3 and 4, the pikes of the voltages in the second and third transitory, go out to the admissibility region of voltage. Only in this case, the different inital condition have influence on the voltage in the second and third period. It means, higher is the value of initial condition, longer is the transitory.

- The problems of the PI control can be avoid if are used different values of the proportional and integral actions. In facts, in a particular range of values, the evolution of node can be bounded into the admissibility region and can ensure the convergence to the reference of the voltage.

- The Pi control represent the best solution in order to obtein a perfect convergence of the voltages to the various references. Furthermore, with the variation of the P and I gains, is possible to ensure some critiacal condition to the voltages of the nodes. In facts, the PI control is the only one who can give the possibility to reduce the pikes of voltages and taken into the admissibility region.

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