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Review article

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Excitation System, Proportional and Integral Controls of a Synchronous Generator for Reducing Adverse Impacts to Power System from Voltage Fluctuations

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Abstract: The project analyzes the voltage fluctuations caused by any disturbance in a power system and minimizes the oscillations by controlling the excitement field using a feedback control loop. Adequate numbers of journal papers and literature materials were researched and reviewed to understand the principles of generator excitation and investigate various control systems which can be worked upon to keep the voltage output stabilized. It is known that Automatic Voltage Regulator cannot respond to the fluctuating generator voltage output fast enough resulting in voltage drop and other adverse effects in power system. Therefore, the project mainly considers the operation of AVR and verifies the improvement in the response time of the control system when a PI controller is added to the loop using EMTP-ATP. Due to unfamiliarity with using the TACS elements in ATP, there were problems in running the simulations without errors and even after that the solutions were intricate. But we were able to overcome the issue and generate the required output. For the project, the automatic voltage regulator control loop was developed and modelled in EMTP-ATP using transfer function blocks and the voltage regulation concept was used to control the excitation of a generator. The model uses transfer function blocks to mimic the functions of AVR, Exciter, Generator and Sensors. Separate cases were run for the system – one with no load changes and one with load changes. The fluctuations in voltage output of generator due to load changes, which overshoot by around 10%, were stabilized in 4 seconds and set to steady state value. A three-phase test system model was also developed to check the functioning of the exciter system for proper model of synchronous generator. The system also includes transmission lines and loads which are connected using switches. The voltage and associated parameters were selected to represent a basic transmission system and an LCC template is used to simulate the transmission line. TACS models were used for coding the AVR control loop of the exciter and defining the machine parameters. Both the cases of increase and decrease of load were tested by opening/closing the switches at different times and disturbances were observed in the voltage output. Here too, the bus voltage was stabilized effectively rendering it to steady state value.

Keywords: proportional integral control, voltage regulation, power system, synchronous generator, AVR control loop, TACS element, PI controller.

1. Introduction

With the current power systems becoming bigger and more complex, the chances for large scale disturbances are more likely to occur which may cause blackouts and financial losses. These disturbances could be due to sudden increase in load, poor coordination between the generation companies and distribution companies, any type of equipment failures and contingencies which are unexpected. This may result in low value of voltage, voltage stability issues, frequency getting out of synchronization and swaying in the active and reactive power. When such disturbances occur, some of parameters mentioned before could change, resulting in change in the electrical power transferred to the load which can be observed from equation (1) [1] [2].

$$P_g = \frac{E_g V_L}{X} \sin\delta \qquad (1)$$

Where E_g is the internal voltage of the generator is proportional to the excitation current, V_L is the voltage of the load, X is the reactance between the load and the generator and δ is the angle by which the internal voltage leads the load voltage. Normally, the average value of the mechanical power input should be equal to the average value of the electrical power given by the equation above. When there is any disturbance in the system, the electrical and mechanical power are not equal anymore. When there is any sudden increase in the load, the mechanical power may fall short causing a relative decrease in the angular velocity. Such variations in the velocity change the angle of the rotor and gives rise to fluctuations in the three-phase power flow or power swings [3] [4].

Synchronous Generator

Synchronous generators are cylindrical rotors with a uniform air gap with reactance remaining the same which is independent of rotor position. While, with salient pole machine air gaps are non-uniform giving rise to asymmetry which is along two axes namely field pole axis (d-axis) and quadrature axis (q-axis). The axis through the field poles and through inter polar space are shown in fig.1. The reactance associated with the direct-axis is termed d-axis synchronous reactance whereas other part is quadrature axis synchronous reactance.

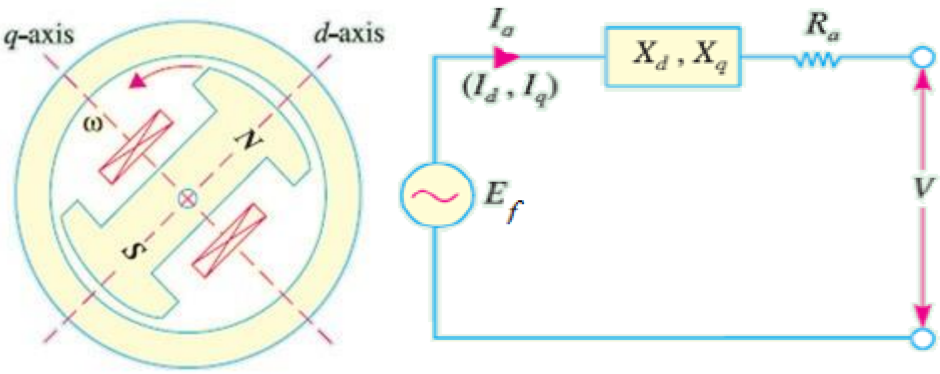
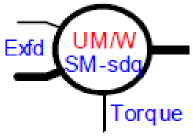


Figure 1: q and d axis of salient pole machine and Equivalent circuit [5]

Field and armature mmf act on along the d-axis while armature mmf acts along the q-axis. Thus, magnetic reluctance is low along d-axis as compared to q-axis.

Table 1: ATPDraw synchronous generator [6]

Windsyn	WISIND/ WISSYN		UM-MACHINE TYPE 1, 3, 4	Universal machine with manufacturers data input.

In the simulation of synchronous generator in this study a Universal Machine with manufacturers data input has been used which is named as Windsyn in the machines block in the software package. A salient pole configuration with d-q axis forms the selection of type of UM-machine.

Excitation System

Synchronous generators are one of the most important parts of the electric power system since it used as the electrical source in almost every type of power plant. A generator converts mechanical torque into electrical energy and for this conversion of energy it requires excitation. Generator excitation is important because it regulates the voltage and reactive power outputs of the generator and by extension, affects stability of the whole power system. The exciter is usually a separate generator (AC or DC) which supplies excitation current to the field winding of the generator. The excitation system has two main components – an Automatic Voltage Regulator (AVR) which controls the exciter during steady state operation and a Power System Stabilizer (PSS) which compensates for the voltage oscillations during disturbances by acting as a supplementary control. The project focused on the AVR part of the excitation control to check any disturbance in system namely load change [7] [8].

Automatic Voltage Regulation

AVR plays an important role in regulation of the generator terminal voltages in desired limits. The need of regulation arises due to dynamic behavior of demand. With increase in the demand the frequency and voltage of generator drops as the load on generator-turbine increases. In such case, with no regulation of terminal voltage, the voltage drops at user end leading to poor customer service. Fig. 2. shows a typical AVR system. In order to regulate the voltage in power stations, excitation of the machine is controlled. The substations employ voltage regulation by use of synchronous compensators whereas at the users, it is performed by use of synchronous motors and series/shunt capacitor banks [9].

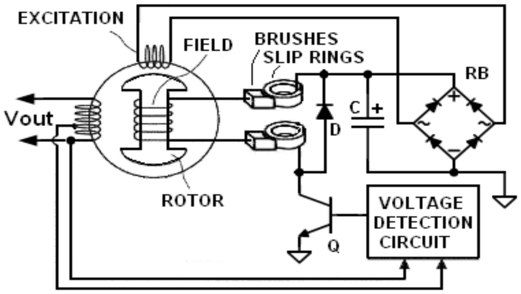


Fig. 2: Automatic voltage regulation [5]

In fig 3 a single phase is supplied to automatic voltage regulator which is generally coiled inside stator slots [5]. This system can be transformed into a block diagram with controller, amplifier, exciter, generator and its feedback control using sensor. This is demonstrated in fig.3.

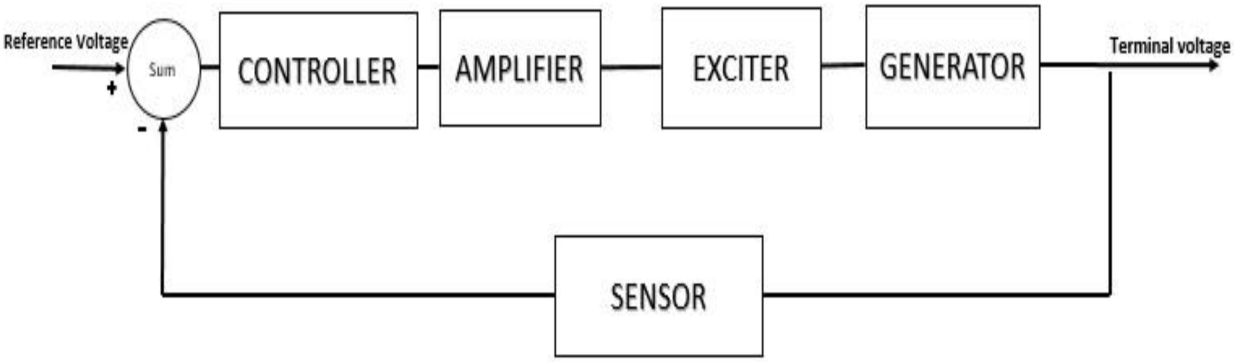


Figure 3: Automatic Voltage regulation [10]

The blocks as shown in fig.3. can be modelled using their transfer functions. The models for exciter such as IEEE DC1A and IEEE ST1A can be used to evaluate the results for voltage regulation. Although, several SIEMENS, NEPLAN models for excitation system can be used for analysis but simplified models in [11] and [12] were used. The voltage regulators are categorized as: direct acting, pulsed and quiescent. In direct acting, resistance varies in the field windings by use of rheostat type [13]. In pulse regulator, a pulse of current flows through the field winding which can either vary in magnitude or frequency to provide desired terminal voltage [7]. Quiescent regulators consist of both direct-acting and pulse ensuring effective operation.

Need of voltage regulation

The permissible tolerance for voltage variations for various user ranges within maximum of + or – 5% [11]. Anomalous behavior in voltage leads to damages in devices and equipment connected in the system. The operating conditions of various sections in the system are not similar hence, AVR is needed during the rise in load current. Mainly the controllers are classified into conventional and unconventional. In conventional controllers, mathematical models must be known to design the controllers. P, PI, PID and PD controllers are types of conventional ones.

Field Excitation and Exciters

The exciters feed current to the field windings by using slip rings and brushes as seen in fig.2. The power of the generator determines the power of the excitement. The power factor of the machine varies with the extent of DC excitation. Under excitation leads to lagging power factors while in over excited state the power factor increases. The frequency of exciter is two to three times the generator voltage. Brushless excitation is often employed to reduce the wear and tear, heating losses. A schematic connection of exciter with synchronous generator field windings is shown in fig.4.

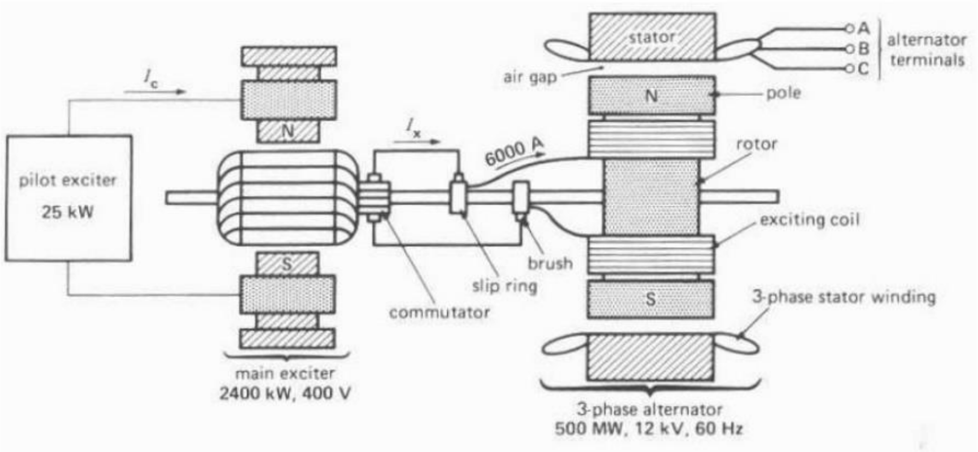


Figure 4: Synchronous generator with DC exciter [1]

In fig.4. pilot and main exciters are connected to synchronous generator using slip rings and brushes allowing flow of excitation current. The use of main and pilot exciter ensures quick response to voltage variations [13].

Proportional-Integral Controller

PI controllers eliminate the forced oscillations and the steady state error. Integral components in controllers give negative impact on the promptness of response and the system stability. Thus, with PI controller speed of response is not improved [14]. Although derivative control addition improves reaction time (i.e. detect future error) but PI controllers are widely used in industry. With the increase in proportional control (K_P) the accuracy of the system improves with small problems with stability. There is a significant decrease in steady state error with an increase in integral constant (K_i). Tuning of the controller is needed to obtain the desired response. The parameters are adjusted by watching the parameters in the system with respect to changes in K_p and K_i. Manually, these values can be set as in particular, K_p =0.00318671 and K_i=0.04186340. Although, there are several methods for tuning controllers such as Ziegler Nichols [14] tuning and software methods, here with simulation manually values have been taken.

2. System Modelling

a. Automatic Voltage Regulator

The AVR rule is to maintain generator terminal voltage at specified levels. The four main components of the AVR system are amplifier, exciter, generator and sensors. The mathematical model and transfer functions of these components along with the PI controller used are given.

Amplifier Modeling

The amplifier is modeled using its transfer function as shown in (2) [1]

$$\frac{V_r(s)}{V_e(s)} = \frac{K_a}{1+T_a s} \tag{2}$$

The constant K_a ranges between 10 to 400 and time dealy $T_a$between 0.02 to 1 s [1].

Exciter modeling

The DC excitation system transfer function is shown in (3) [15]

$$\frac{V_f(s)}{V_r(s)} = \frac{K_e}{1+T_e s} \tag{3}$$

The constant $K_e$ranges between 10 to 400 and T_e ranges up to 1 s.

Generator modeling

The terminal voltage of the generator in relation with generator input voltage is used to identify its transfer function as shown in (4) [15]:

$$\frac{V_t}{V_i} = \frac{K_g}{1+T_g s} \tag{4}$$

Here, constant $K_g$ranges between 0.7 to 1 while T_g ranges up to 1 s.

PI controller modeling

A PI (Proportional Integral) controller equation in s-domain is shown in (5) [15]

$$\frac{V_{out}(s)}{V_{in}(s)} = K_p + \frac{K_i}{s} \tag{5}$$

K_p represents the proportional constant and K_i represents integral constant. In particular, $K_p = 0.003681$ and $K_i = 1$.

Sensor

A sensor block is modeled as an integrator providing feedback to compare with the reference voltage. It contains a detection tool in determining the response time of the control models [9].

Load Model

DC step functions are used to simulate loads by varying the time of exposure to the generator.

3. Case Studies and Discussion

The project includes simulation of the AVR operation in the following two stages

a. Transfer Function Model

For this project, first the transfer function system is modelled in EMTP-ATP and is equipped with control model of AVR and PID which gives a quick response in controlling the changes in voltages caused by the changes in system load.

- A no-load test was carried out for an AVR scheme with a proportional-integral (PI) type controller as shown in figure 5. This was done to evaluate the performance of the excitation control system with typical test signal (voltage step) and check the characteristic response. The test evaluates the response time and stabilization time of the excitation control system.

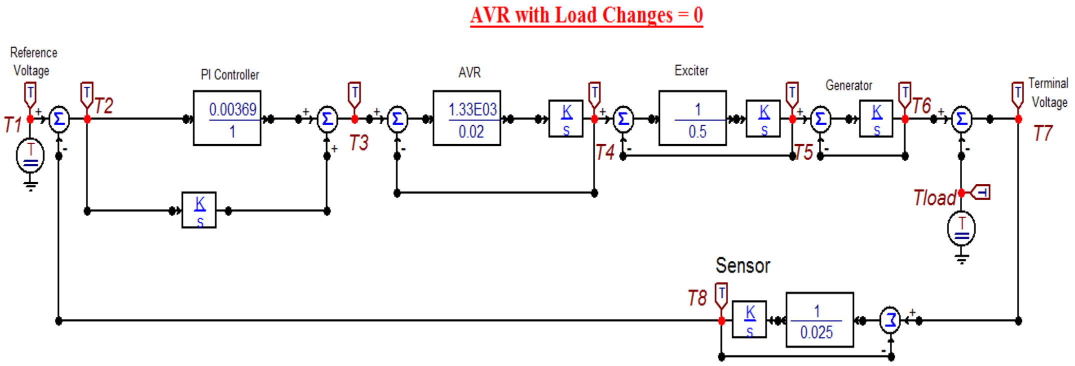


Figure 5: AVR Simulation with PI control during normal conditions

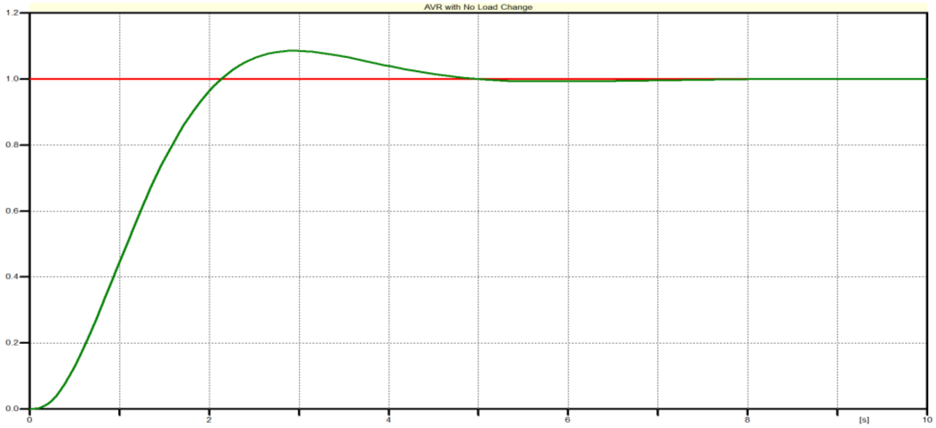


Figure 6: Output Voltage (p.u.) vs time (sec)

In fig. 6 the magnitude of generator output voltage to the reference voltage 1pu, for Kp = .00318671 and Ki = 0.04186340, overshoots by 10% before setting time of 5 seconds. After a slight overshoot of 10%, the output voltage sets to a constant value of 1pu. The response for every element i.e. the first error signal, the amplifier response and the first order generator response have been attached as *Appendix C*.

The load test was then carried out to evaluate the performance of the excitation control system with typical test signal (voltage step) and check the characteristic response. The load signal was given in the form of different step signals to mimic the effect of change in load. The test evaluates the damping characteristics and the response time of the excitation control system where there is sudden increase or decrease in load.

AVR with PI controller

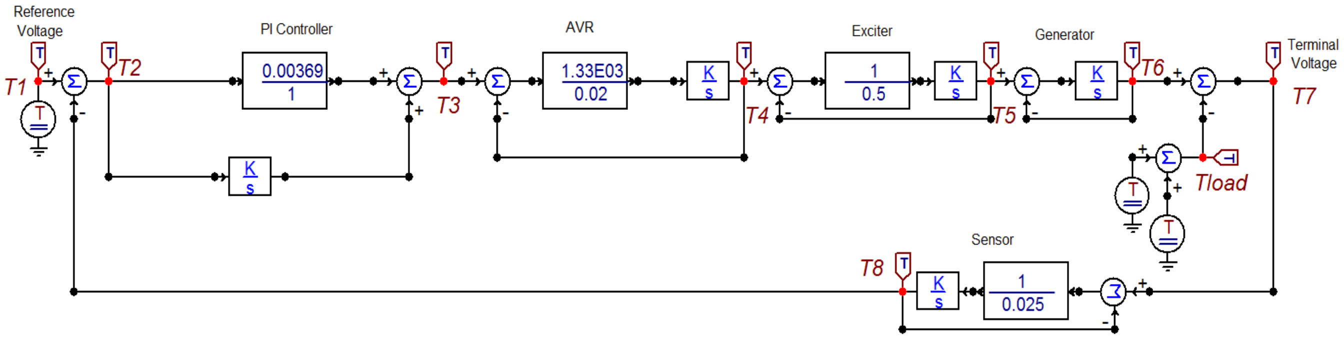


Figure 7: AVR Simulation with PI control on load condition

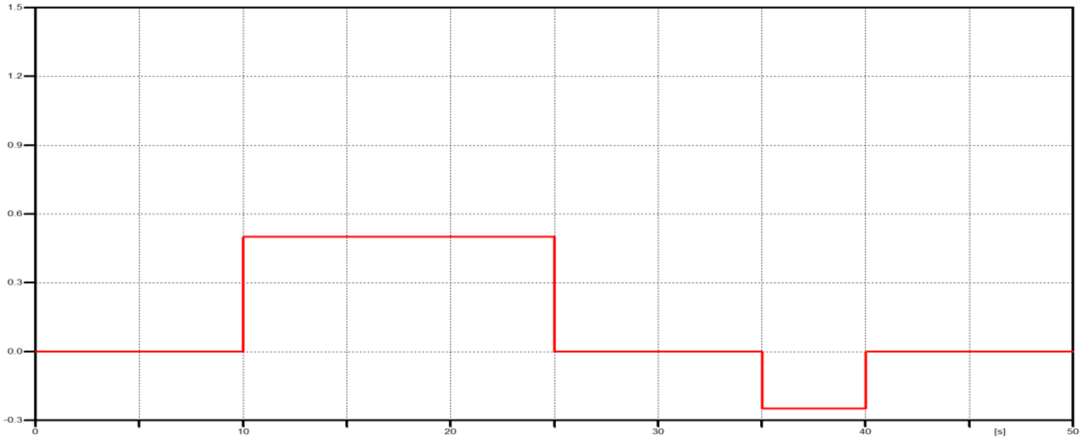


Figure 8: Load Changes (p.u.) vs time (sec)

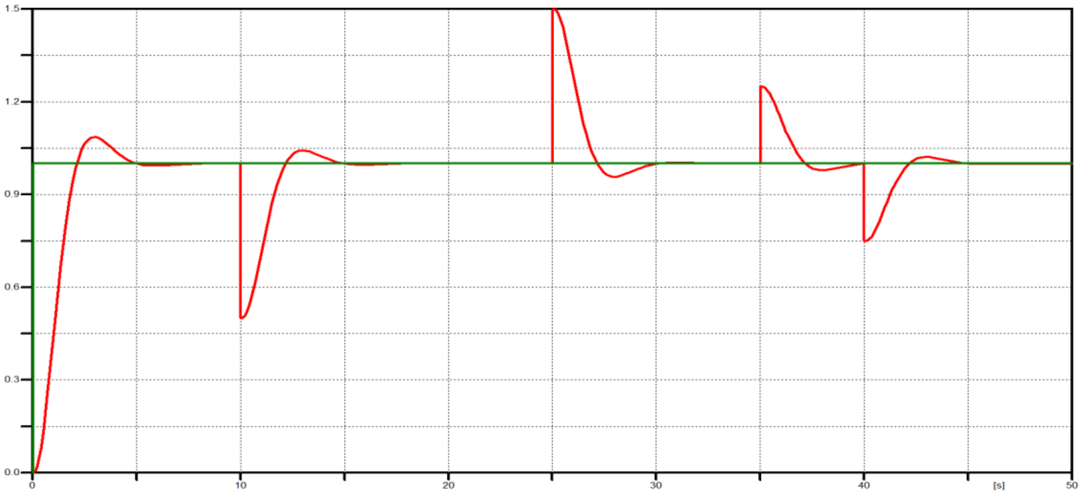


Figure 9: Voltage changes vs Time

Simulation of AVR with PI controller for load changes

The above graphs (fig 8, 9) simulate the generator voltage output using AVR with PI controller, when there is a disturbance, which is change of load in this case. With the addition of 0.5pu load and reduction of 0.2pu load, change occurs in the output voltage of the generator but is brought down to the reference value with only one cycle of fluctuation. The response for every element i.e. the first error signal, the amplifier response and the first order generator response have been attached as *Appendix C*.

Power System Model

After verifying the transfer function model, a three-phase test system was modelled in EMTP-ATP having a synchronous generator, transmission lines, and loads. A UM/W generator is used which has a feedback loop running through the exciter control system. Four transmission lines L1, L2, L3 and L4 carry power to loads LD1, LD2, LD3, LD4 and LD5 from generating source G. The governor system has been neglected as part of this study.

ST1A type excitation system has been used using user defined models in ATP with its model parameters as shown in *Appendix D*. The models for frequency and rms value measurements are shown in *Appendix A*. Generator terminal phase A (shown red) is used as feedback to the exciter for controlling the excitation to maintain desired terminal voltage. Generator G and transmission line parameters are also shown in *Appendix B*. With switching between S1 and S2, S3 and S4, several cases of excitation control have been studied. The LCC section values along with load values for LD1, LD2, LD3, LD4 and LD5 are shown in *Appendix A* and *B* respectively.

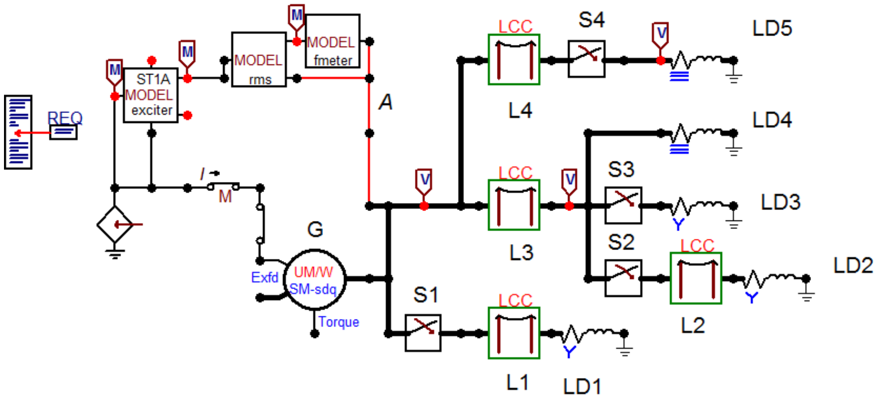
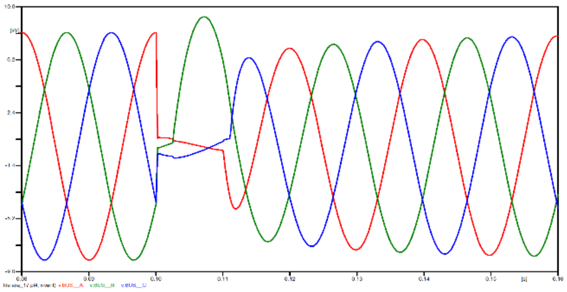
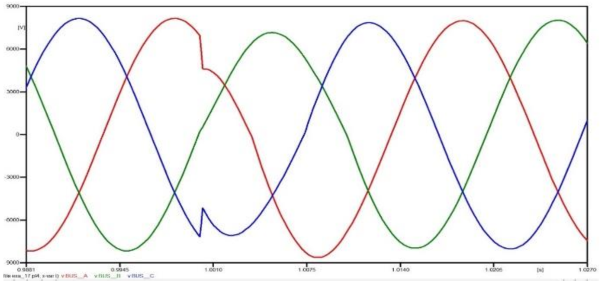


Figure 10: System Model with Excitation System for Synchronous Generator

Switch	Open time (s)	Close time (s)	Time for voltage stabilization with connected loads (ms)
S1	-1	10	-
S2	0.1	-1	12
S3	-1	1	2
S4	0.5	-1	3

Table 2: Switching Operation for simulating load changes





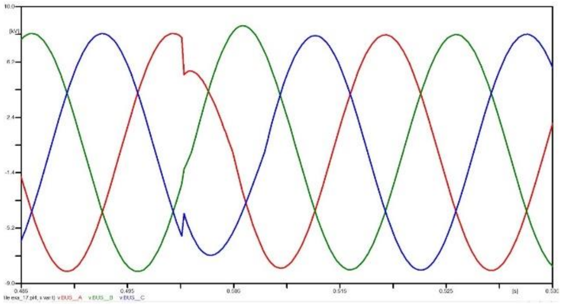


Figure 11: Voltage disturbance and stabilization after removing first load (S1)
Figure 12: Voltage disturbance and stabilization after adding second load (S3)
Figure 13: Voltage disturbance and stabilization after removing third load (S4)

As seen in the graphs, the graphs indicate voltage disruptions when the loads are switched followed by its stabilization of voltage with an average time of 2.5ms for loads connected with S3 and S4 while for load connected with S2, 12ms. The increase in time for stabilization is due to the higher level of increased loading with line section L2 and load LD2. Thus, stabilization depends on the extent of the loading conditions for the system. Moreover, with no switching of load LD1 with S1 results in no variations in the voltage.

4. Conclusion

A voltage regulator is not only useful, but also an important accessory to generating equipment. It may be safe to say that the operation of some systems would be impossible without automatic control. A PI controller for controlling the excitation system has been designed in such a manner that it takes the least time to damp the oscillations and stabilize the generator terminal voltage. A simplified approach used to study excitation control in ATP-Draw using transfer functions for various components gave results in line with another approach using machine and excitation models. An analysis presented for changes in loading conditions for both the models suggest extent of loading and its switching determines the time for excitation system to activate and resolve the terminal voltage variation problem by stabilization. For a power engineer, presented results have significance during switching and load change operations occurring abnormally due to faults.

5. Discussion and Future Scope

An approach with the use of PID controllers and detailed models for various sections in the system can be used for excitation system studies. Various other ATP-Draw models for synchronous generators such as Synchronous Wi and SM59/58 can be used for analysis. Also, with changes in excitation systems such as

IEEE DC1A, terminal voltage can be studied. AVR works effectively for steady state operation but for major disturbances, PSS is used. A model for PSS could be added to the system which controls the excitation using reactive power as its input. For using the combination of AVR and PSS effectively, a governor model could be modelled for parameter inputs to the controllers.

6. References

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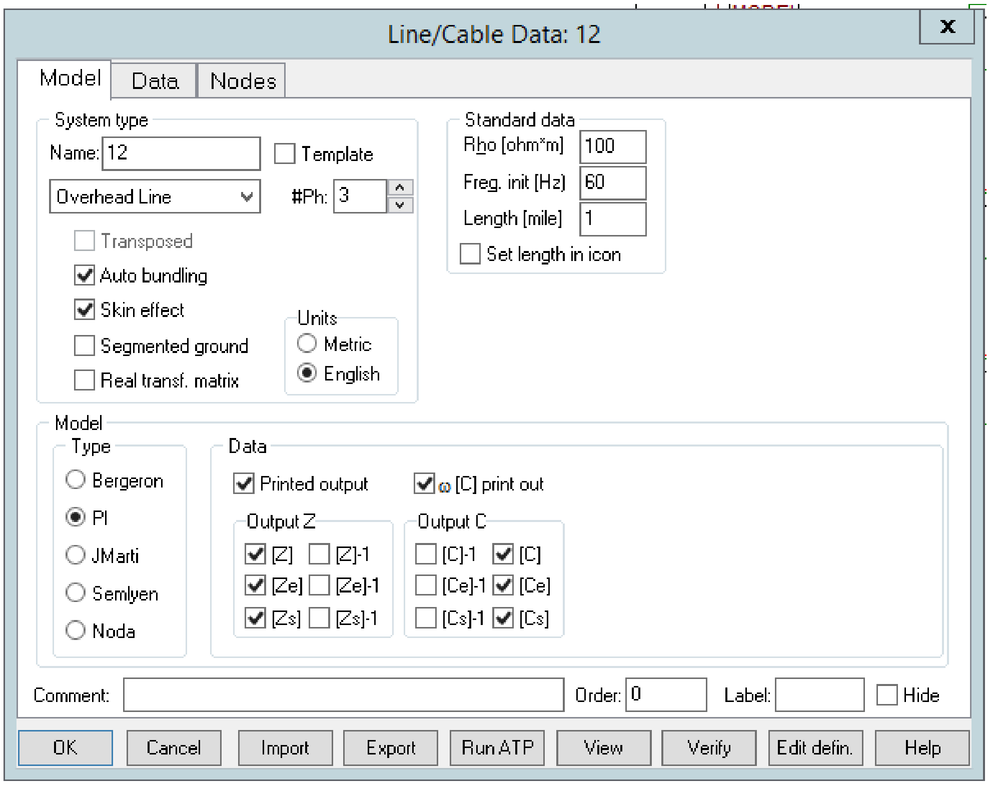
APPENDIX A

LCC data



Line/Cable Data: 12

System type
Name: 12
☐ Template
Overhead Line
#Ph: 3
☐ Transposed
☑ Auto bundling
☑ Skin effect
☐ Segmented ground
☐ Real transf. matrix

Units
○ Metric
● English

Standard data
Rho [ohm*m] 100
Freq. init [Hz] 60
Length [mile] 1
☐ Set length in icon

Model

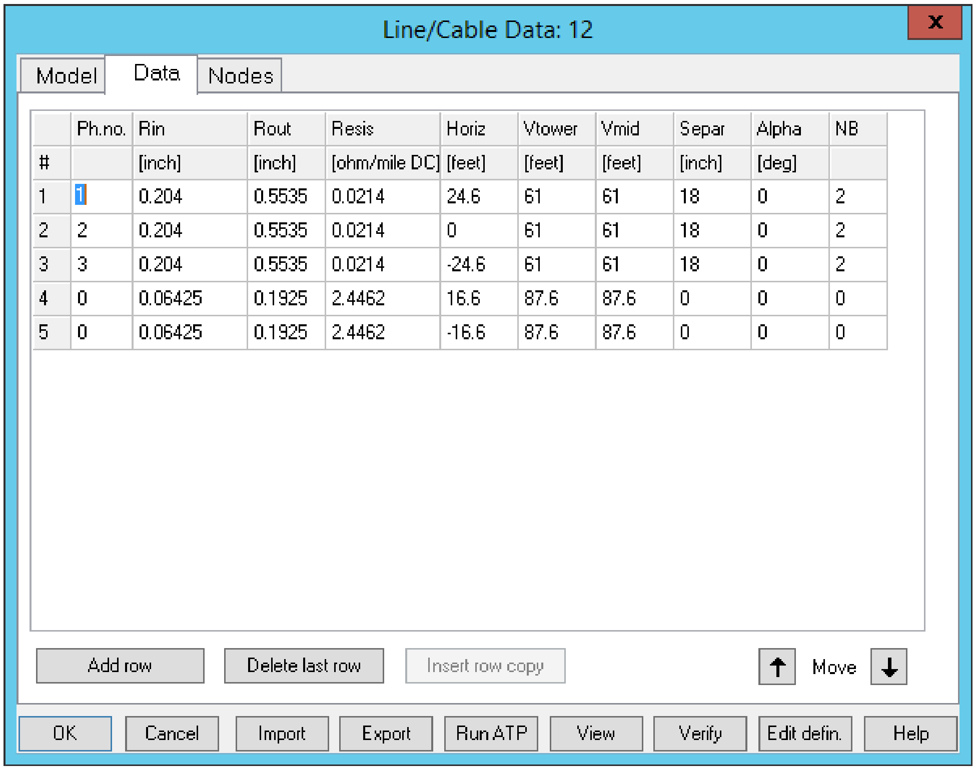
Type
○ Bergeron
● PI
○ JMarti
○ Semlyen
○ Noda

Data
☑ Printed output
☑ ω [C] print out

Output Z
☑ [Z] ☐ [Z]-1
☑ [Ze] ☐ [Ze]-1
☑ [Zs] ☐ [Zs]-1

Output C
☐ [C]-1 ☑ [C]
☐ [Ce]-1 ☑ [Ce]
☐ [Cs]-1 ☑ [Cs]

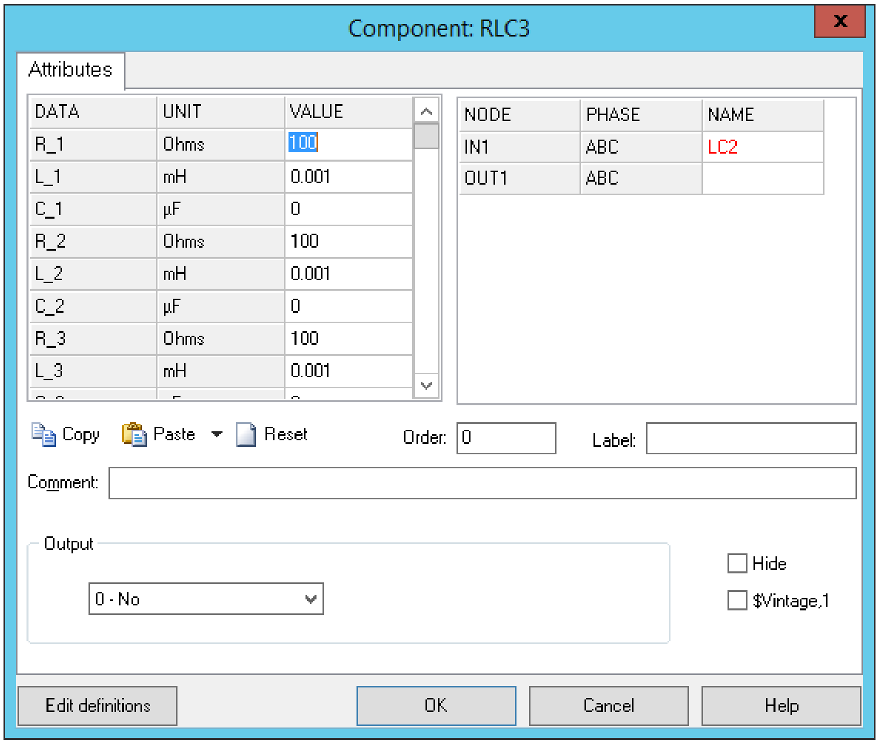
Comment:
Order: 0
Label:
☐ Hide



Line/Cable Data: 12

#	Ph.no.	Rin [inch]	Rout [inch]	Resis [ohm/mile DC]	Horiz [feet]	Vtower [feet]	Vmid [feet]	Separ [inch]	Alpha [deg]	NB
1	1	0.204	0.5535	0.0214	24.6	61	61	18	0	2
2	2	0.204	0.5535	0.0214	0	61	61	18	0	2
3	3	0.204	0.5535	0.0214	-24.6	61	61	18	0	2
4	0	0.06425	0.1925	2.4462	16.6	87.6	87.6	0	0	0
5	0	0.06425	0.1925	2.4462	-16.6	87.6	87.6	0	0	0

APPENDIX B
Load data



Component: RLC3

DATA	UNIT	VALUE
R_1	Ohms	100
L_1	mH	0.001
C_1	µF	0
R_2	Ohms	100
L_2	mH	0.001
C_2	µF	0
R_3	Ohms	100
L_3	mH	0.001

NODE	PHASE	NAME
IN1	ABC	LC2
OUT1	ABC	

Order: 0

Label:

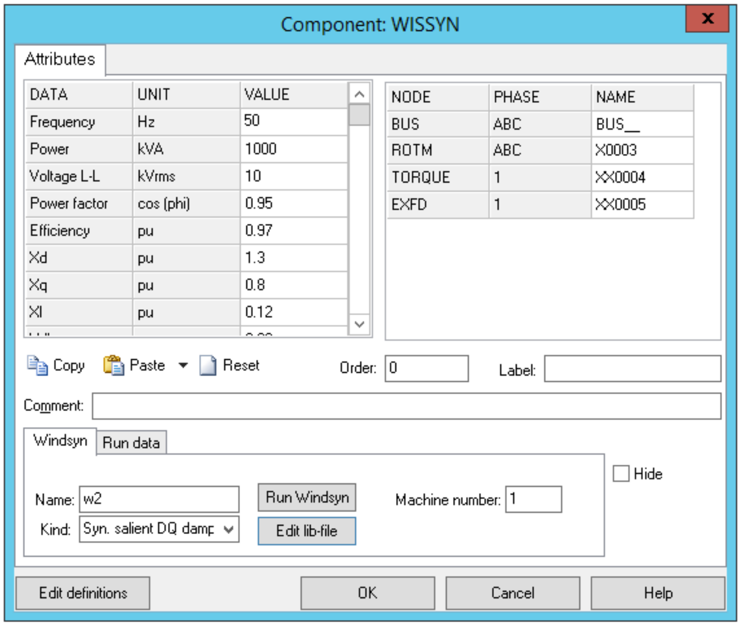
Comment:

Output: 0 - No

☐ Hide

☐ $Vintage,1

Generator data [6]



DATA	UNIT	VALUE
Frequency	Hz	50
Power	kVA	1000
Voltage L-L	kVrms	10
Power factor	cos (phi)	0.95
Efficiency	pu	0.97
Xd	pu	1.3
Xq	pu	0.8
Xl	pu	0.12

NODE	PHASE	NAME
BUS	ABC	BUS__
ROTM	ABC	X0003
TORQUE	1	XX0004
EXFD	1	XX0005

Order: 0

Label:

Comment:

☐ Hide

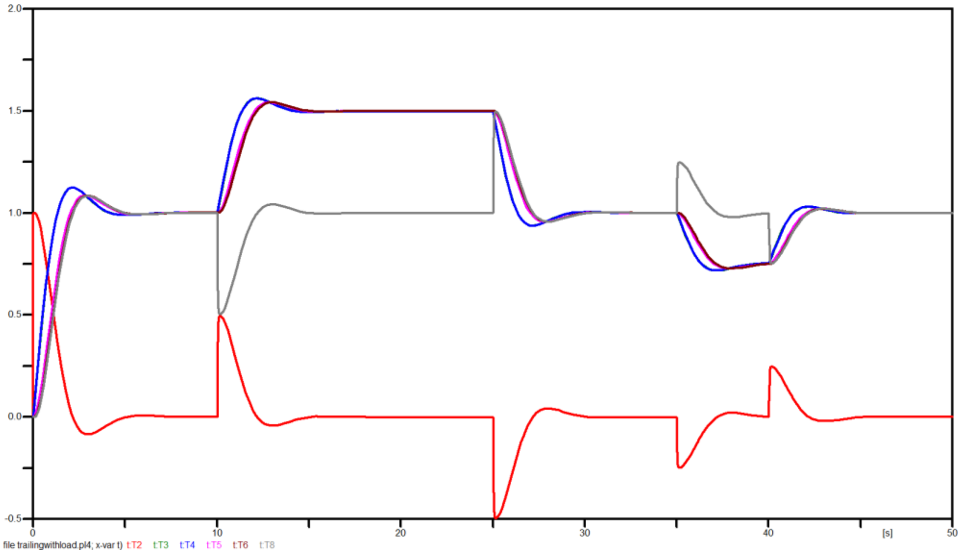
Name: w2

Kind: Syn. salient DQ damp

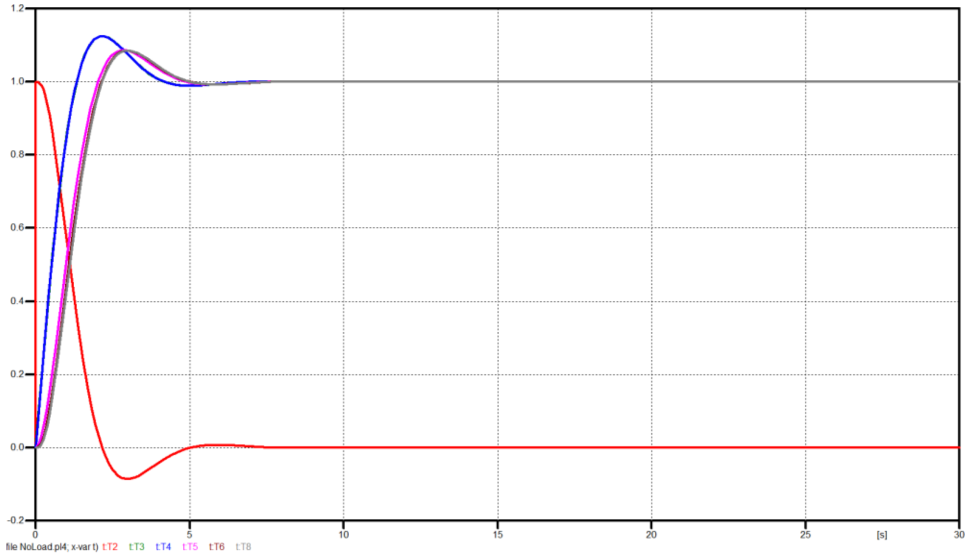
Machine number: 1

APPENDIX C

Voltages at successive nodes with loaded condition



Voltages at successive nodes without load



APPENDIX D

Exciter Model (IEEE ST1A) [6]

```
MODEL EX_ST1A
DATA Vref,VTpu,Tr,Tc,Tb,Ka,Ta,Vuel,Voel, Klr, Ilr, Kf, Tf, VRmax,VRmin, Kc, EFDref,IFDref
INPUT VT, Ifd, Vs, If0
OUTPUT Efd
VAR x1,x2,x3,x4,x5,x6, Efd,Vc,IFDpu,Efd0
HISTORY
x1 {dflt:0},x2 {dflt:0},x3 {dflt:0},x4 {dflt:0},x5 {dflt:0}, x6 {dflt:0},
Vc {dflt:0}, VT {dflt:0}
INIT
  Efd:=0
ENDINIT
EXEC
  if T<2*timestep then  --Special trick to obtain the initial field voltage
    Efd0:=-If0*0.01
  else
    IFDpu:=-IFD/IFDref
    --Vc:=VT/(1+Tr)
    cLaplace(Vc/VT):=(1/VTpu|s0)/(1|s0+Tr|s1)
    cLaplace(x6/x5):=(Kf|s1)/(1|s0+Tf|s1)
    x1:=Vref-Vc-Vs-x6
    cLaplace(x2/x1):=(1|s0+Tc|s1)/(1|s0+Tb|s1)
    cLaplace(x3/x2):=(Ka|s0)/(1|s0+Ta|s1)
    x4:=x3-(IFDpu-Ilr)*Klr
    x5:=max(x4,Vuel)
    x5:=min(x5,Voel)
    Efd:=x5 {min:VT/VTpu*VRmin max:VT/VTpu*VRmax-Kc*IFDpu}
    Efd:=Efd*EFDref+0*Efd0
  endif
ENDEXEC
ENDMODEL
```

RMS value measurement [6]

```
MODEL rms_meter
  DATA   xrms_ini {dflt:-1} -- initial rms value
  INPUT  freq      -- monitored frequency
         x         -- monitored signal
  VAR    xrms      -- rms value of monitored signal
         x2        -- internal, x*x
         ix2       -- internal, integral of x2
         period    -- 1/freq
  OUTPUT xrms
  DELAY CELLS(ix2): 1/2/timestep +1
  INIT
    histdef(ix2) := 0
    integral(x2) := 0
    IF xrms_ini <0 THEN xrms:=0 ELSE xrms:=xrms_ini ENDIF
  ENDINIT
  EXEC
    period       := recip(freq)
    x2  := x*x
    ix2 := integral(x2)
    IF t>period THEN
      xrms:= sqrt((ix2 - delay(ix2, period))/period)
    ENDIF
  ENDEXEC
ENDMODEL
```

Frequency value measurement [6]

```
MODEL fmeter
  DATA   f0      -- initial frequency [Hz] (used until the 2nd zero-crossing)
         band    -- max acceptable change [%]
  INPUT  x       -- monitored signal [any units]
  VAR    f       -- measured frequency [Hz]
         txing   -- time of last detected zero-crossing
         xprev   -- previous value of signal
         dtmin   -- minimum sampling half-period
         dtmax   -- maximum sampling half-period
         a       -- temp variable
  OUTPUT f
  INIT
    f     := f0
    txing := -2
    xprev := x
    dtmax := 0.5/(1-band/100)/f0
    dtmin := 0.5/(1+band/100)/f0
  ENDINIT
  EXEC
    IF txing = -2 THEN txing := -1
    ELSIF txing = -1 AND xprev*x <=0 THEN txing:=t
    ELSIF xprev*x <=0 AND t-txing >= dtmin AND t-txing <= dtmax THEN
      a := backtime(x, 0)
```

```
      f := 0.5/(a-txing)
      txing := a
    ENDIF
    xprev := x
  ENDEXEC
ENDMODEL
```