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Research Paper

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Performance Analysis of TCSC with Firing Angle Determination Based on Random Forest Algorithm

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***Abstract*—** In order to meet the rising power demand, the options are to increase the generation and transmission facilities or to install more power plants. But installation of new power stations is costly matter and needs huge investment. So, it is desired to increase the power transfer capacity of the existing system. In the proposed work the use of fixed capacitors and Power -Electronics-based series FACTS device TCSC are done to increase the power transfer capacity of the system. The key contribution of this paper is the firing angle prediction by Random Forest Machine Learning Algorithm (RFMLA) for the various modes of TCSC. The trained data of input power and angle is loaded into the system and then firing angle prediction is done over the new data. Many decision trees are created for the input power and firing angle using MATLAB coding. The final value of firing angle is selected by the algorithm. The power flow and THD results are shown. FFT analysis tool in Powergui block is used to calculate THD voltage without compensation and then after using TCSC, combination of both FC and TCSC. The main issues and challenges in today's smart power systems are meeting power demand and power quality problems like voltage sag and voltage swell created due to disturbances or faults, stability, contingency and congestion management with taking care of environment. The TCSC is capable of meeting all these challenges. The novelty here is the appropriate prediction of firing angle based on RFMLA.

***Keywords*—** *Capacitor, Inductive ,Power quality, Total Harmonic Distortion, Voltage*

Nomenclature

L	TCSC Inductor
C	TCSC Capacitor
TCSC	Thyristor Controlled Series Capacitor
FC	Fixed Capacitor
k	degree of series compensation
α	Firing angle
FA1	Firing angle 1 for module 1 of TCSC
FA2	Firing angle 2 for module 2 of TCSC
TCSC	Thyristor controlled series capacitor
RFMLA	Random Forest Machine Learning Algorithm
MLAs	Machine Learning Algorithms
DT	Decision tree
$\overline{w}$	Resonant Factor
X_{TCSC}	TCSC Reactance
X_{system}	Reactance of the system
X_L	TCR Inductive Reactance in ohms
$X_L(\alpha)$	Variable TCR inductive reactance in ohms
δ	Transmission angle
THD	Total Harmonic Distortion
SSR	Sub Synchronous Resonance
FFT	Fast Fourier Transform

I. INTRODUCTION

The various parts of the power system are generation, transmission, and distribution. There is rapid increase in the demand of electricity due to fast industrial development and population growth. The generating stations are located far away from load centres due to economic, environment and safety reasons. The transmission lines have to carry power from generating stations to load centres. There is lack of generation and transmission facilities, so the existing system is used to transfer more power demand. This causes overexploitation of the present system and gives rise to stability problems. The power transfer capacity of the existing transmission lines can be increased by using Fixed Capacitors (FC) by varying the impedance of the transmission lines, but there are Sub -Synchronous Resonance ,wear and tear, slow response problems with FC. In this situation FACTS device TCSC is used to control power flow in the system[1].It is economical also as it does not require any form of interface such as dc link ,converters, storage device and high voltage transformers. With TCSC the transmission lines can be operated near thermal and stability limits without violating the system security .The equation for active power flow is given by P = $\frac{V_{s*}V_r}{X_{system}+X_{TCSC}}$ Sinδ . The sensitivity of active power (P) with system reactance X_{system} is given by the relation $\frac{\partial P}{\partial X_{system}} = \frac{-P}{X_{system}+X_{TCSC}}$. The sensitivity of P is high with $X_{system} + X_{TCSC}$.The TCSC reactance (X_{TCSC}) is related with firing angle alpha (α) .The sensitivity of P with α is given by relation $\frac{\partial P}{\partial \alpha} = \frac{-P}{X_{system}+X_{TCSC}} \frac{\partial X_{TCSC}}{\partial \alpha}$ [2],[3].This equation shows the relation between power and firing angle of TCSC. This is the main relation used in this paper. The firing angles for TCSC have been **generated** with different circuits and methods like RF Flip method, Pulse -Generators, fuzzy controller ,Control circuit based on HDL, Arduino. In the present work the firing angle for TCSC is **predicted** using a novel Random Forest Machine Learning Algorithm(RFMLA). Intelligent firing angle prediction for both the inductive and capacitive modes of TCSC are done with this algorithm based on trained data of power flow and firing angle. Three PLL units are used in the firing circuit here. For the calculation of impedance of TCSC, the feedback of voltage and current are used. The novelty of the present paper is the accurate prediction of firing angle with RFMLA. The Machine learning algorithms have extensive computational capabilities and are very fast in producing accurate results. Then various waveforms are plotted with different modes of TCSC. The THD analysis of the system is also done.

II. RELATED WORK

The TCSC cost is given by $C_{TCSC}(Var) = 0.0015.S^2 - 0.7130.S + 153.75$ .Here S is the operating range of TCSC device. The genetic algorithm was used for solving the optimal power flow problem of the system installed with TCSC .The total cost of generation of power without TCSC was 1636.02$/h whereas using TCSC device in the system the cost of power generation was found to be 1633.24$/h. The cost of generation with genetic algorithm based TCSC was found to be 1602.70$/h. The TCSC was designed based on PI controller and performance was analysed at different places of the line such as receiving ,sending and middle of the line[4]. The simulation circuitry was designed using RS Flip Flop and calculations were done for different values of compensation. The waveforms were captured for various parameters of the system with different firing angles. The MLAs were applied in various problems of power system .The MLA based system showed an improvement in efficiency along with minimization of losses. In [5] the more power was generated without harming the environment and with minimum investment with TCSC. The TCSC device consists of capacitor in parallel with a TCR. By changing the firing angle of thyristor, the TCSC is used to provide variable compensation. There are different operating modes of TCSC which are bypass, blocked and vernier modes. In the inductive vernier mode of TCSC the power flow decreases and in capacitive vernier mode the power flow increases[6],[7]. The TCSC Reactance Characteristic Curve between firing angle and reactance shows the inductive, capacitive and resonance regions of TCSC. In the resonance region ,the operation of TCSC is prohibited. The inherent property of TCSC is to improve the power flow and stability of the system[8].

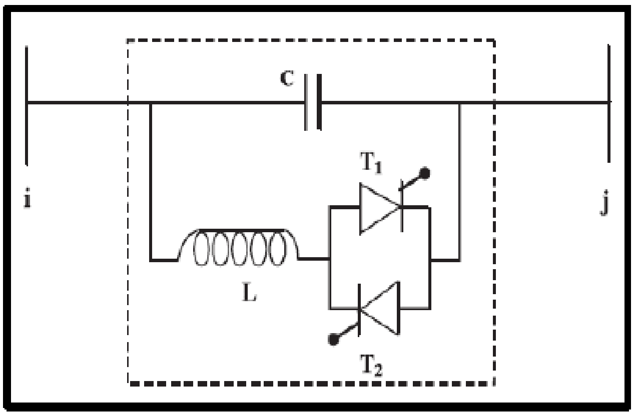

Figure 1.TCSC Model

The RFMLA is a supervised machine learning algorithm which is used for solving classification and regression problems. It is based on ensemble learning technique where a large number of decision trees (uncorrelated) are created for the prediction of accurate ,stable and fast results. The ensemble method is very powerful and flexible due to which the algorithm has high computational capabilities. The decision trees methodology worked well on trained data but not on unseen samples and data [9].This limitation is removed here in RFMLA. The problem of overfitting of data in decision trees is taken care in RFMLA. Diversification and large number of trees are the two main salient features of this algorithm. The decision trees in random forest are highly uncorrelated due to feature randomness property [10].The bootstrapping (bagging)method is used here for producing diverse and uncorrelated trees. The Out of bag error (OOBE) is the number of observations which don't appear in the sample at least once. The OOBE is calculated here with the number of grown trees and is found to be reducing with the number of grown trees[11].

III. METHODOLOGY

3.1 Test System

The series compensation by TCSC is done in the proposed work over 400 kV and 400 km long transmission line. The line is designed for 75% compensation. The value of Inductance /km= 1.044 mH . The total inductance of line for 400 km length is 0.4176 H. The value of total line reactance in ohms is = 131.1929 ohms. For 75% series compensation the value of TCSC capacitor is 32.3503 µF and TCSC inductor is 0.07828 H. The resonance factor is taken as 2. Thus, the resonance angle is 45 degrees. The value of Fixed capacitor is 85 µF. For 90% compensation the values of TCSC Capacitor and inductor are 26.9722 µF and 0.0940 H. For the first 0.5 sec the TCSC is bypassed. FA1 and FA2 are the firing angles to two modules of TCSC .The simulation is run, and various waveforms are observed on the scopes.

3.2 Simulation Diagram

The simulation of the system is performed without installing TCSC and then with TCSC in the system. The various blocks used in simulation are the transmission line, source, load, bus ,scopes, display power and voltage measurement blocks. The simulation is run for 10 seconds. The calculation of TCSC impedance is done based on current and voltage feedback to the system. The TCSC block includes the values of TCSC capacitor and inductor. The TCSC simulation system consists of TCSC ,control system and firing unit blocks. The firing pulses are generated using TCR pulse generator inside the firing unit block. There is a toggle switch for changing the operating modes of TCSC which are the manual, inductive and capacitive modes inside the control system block.

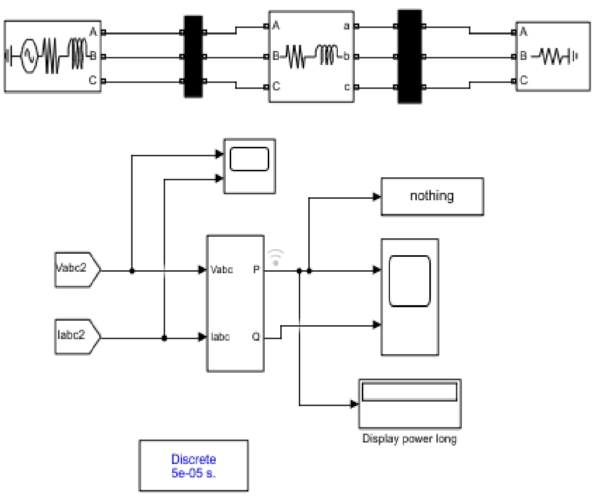

Figure 2. System without any device/Controller

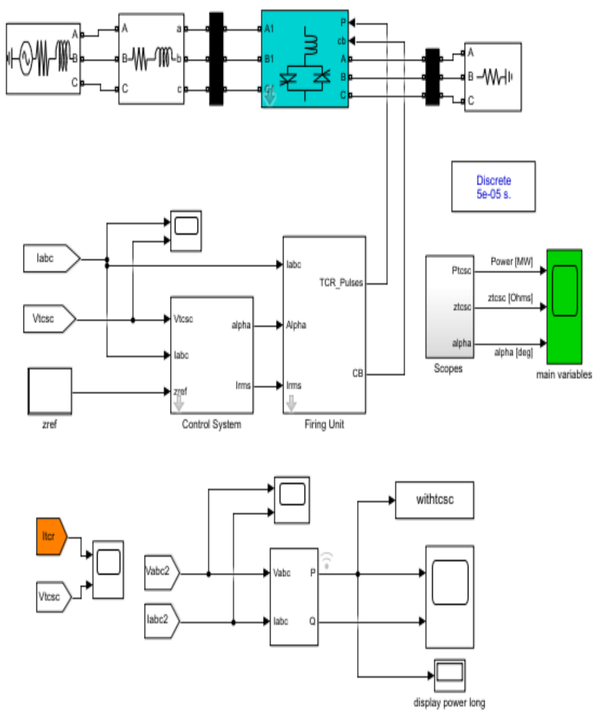

Figure 3. System with TCSC

IV. RESULTS AND DISCUSSION

4.1 Without compensation the active power transfer is 339.44 MW. With TCSC the power flow is given in table 1. The power transfer is increased in the capacitve region and decrease in the inductive region based on firing angle. The TCSC is generally used in the capacitive region for stability and power transfer enhancement.

Table 1 Power Flow with TCSC

Capacitive Region			Inductive Region	
S. No	**Angle (Degree)**	**Power (MW)**	**Angle (Degree)**	**Power(MW)**
1	59	381.90	0	310.86
2	60	381.90	20	286.77
3	65	380.99	25	274.08
4	70	380.52	30	258.65
5	75	380.08	35	232.43
6	80	379.95	40	196.59
7	85	379.90	45	149.93
8	90	379.97	50	97.079

4.2 Machine Learning Algorithms(MLA)

The classification of different MLA is shown in the figure 4. MLAs help the companies in taking better decisions by making accurate predictions. MLAs have revolutionized the way of working and solving complex problems. This is due to no human intervention and easily dentification of patterns and trends which showed continuous improvement. In Supervised MLA the machine is trained first with the data and the final output is predicted based on that trained data. The RFMLA and Decision tree falls under the umbrella of supervised learning[12].

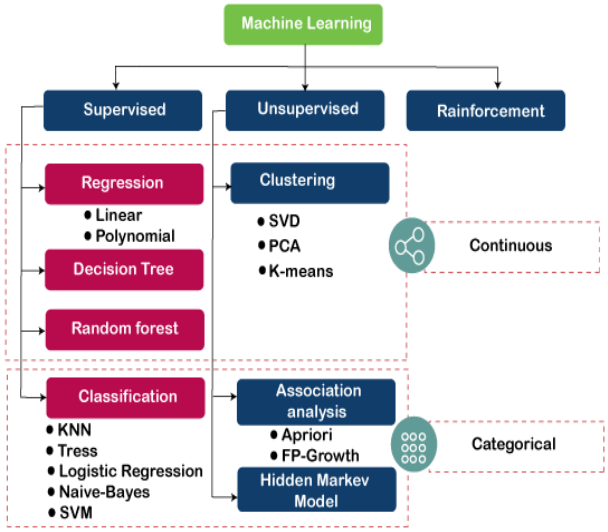

Figure 4. Machine Learning Algorithms[14]

In RFMLA different decision trees (DT)are created on samples of data from the training data. For classification problem the majority of votes and for regression problem the average of votes is taken. The Bagging method is used here for created a forest of random trees. Figure 5 shows the model for RFMLA.

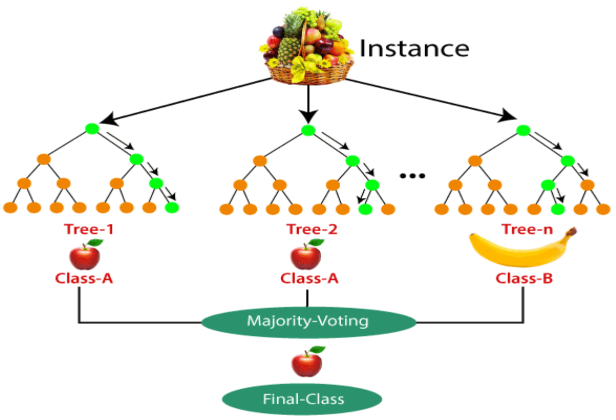

Figure 5. Random forest Model [14]

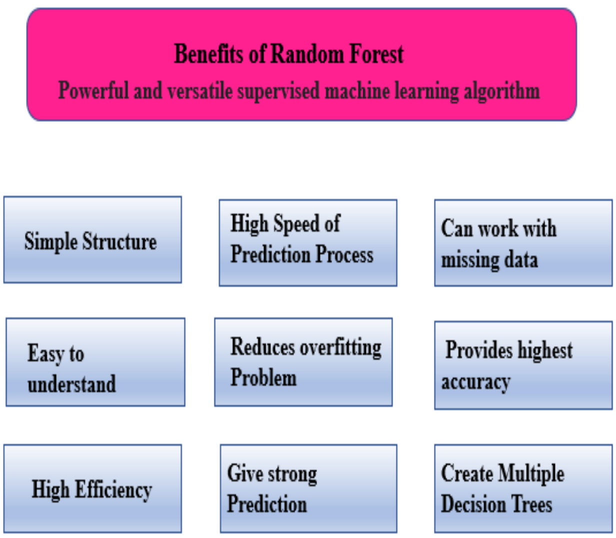

Figure 6. Benefits of Random Forest

4.3 Firing angle prediction in Capacitive mode of TCSC using RFMLA

A Function called generic_random_forests is created in which the variables X,Y, no of bags , classification method is loaded. The data of input power and firing angle according to the characteristic curve of TCSC are loaded into the system. The input power data set contains power values for both inductive and capacitive modes of TCSC. The input variable is X which is the power and output variable is Y which is the firing angle predicted corresponding to the input power. The Power input can be in inductive and capacitive range of TCSC according to reactance characteristic curve. The object used for creating an ensemble of bagged decision trees is treebagger for the present classification problem. The bagging ensemble method is used here for improving the generalization and removing the problem of overfitting. The treebagger is created for selecting randomly subsets of predictors based on random forest algorithm for each decision split .The data of input power and angle is loaded into the system using the command load mydata. The commands from the bagged ensemble program generic_random_forests (X',Y',60,'classification'), predict (BaggedEnsemble, [580]) is used to predict the firing angle which comes out to be 75 degrees for this random power input (580 MW) belonging to capacitive region of TCSC. The result generated from MATLAB is:

```
BaggedEnsemble =

  TreeBagger
Ensemble with 60 bagged decision trees:
                    Training X:              [10x1]
                    Training Y:              [10x1]
                        Method:      classification
                 NumPredictors:                   1
         NumPredictorsToSample:                   1
                   MinLeafSize:                   1
                 InBagFraction:                   1
         SampleWithReplacement:                   1
          ComputeOOBPrediction:                   1
ComputeOOBPredictorImportance:                   0
                     Proximity:                  []
                    ClassNames:          '0'              '10'
```

Figure 7. Tree viewer

The classnames are created for all the firing angles from 0 to 90 degrees in step of 10 degrees.The following decision tree is created by MATLAB for the capacitive mode of TCSC.The input power is compared with different power and finally the angle predicted is 75 degrees .The splitting of node in random forest is based on randomness feature of RFMLA .The input power from the data set is selected randomly and then comparison is done as shown. This randomness feature in RFMLA produces better decision trees and prediction The Classification tree viewer generated from MATLAB using RFMLA is shown in figure 8.

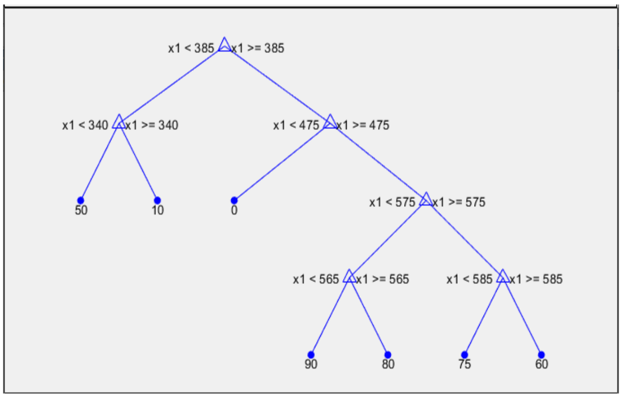

Figure 8. Decision tree Capacitive mode

The same decision tree in a different form generated by MATLAB is given in figure 9. Multiple decision trees are created in random forest. The results of different trees are aggregated, and one final result is produced. The Random Forest is powerful as there is no bias in selecting the feature for splitting the node of decision tree. The training is done on different samples in RFMLA, and this is helpful in reducing the variance which produces better results.

```
Decision tree for classification
 1  if x1<385 then node 2 elseif x1>=385 then node 3 else 10
 2  if x1<340 then node 4 elseif x1>=340 then node 5 else 10
 3  if x1<475 then node 6 elseif x1>=475 then node 7 else 0
 4  class = 50
 5  class = 10
 6  class = 0
 7  if x1<575 then node 8 elseif x1>=575 then node 9 else 60
 8  if x1<565 then node 10 elseif x1>=565 then node 11 else 80
 9  if x1<585 then node 12 elseif x1>=585 then node 13 else 60
10  class = 90
11  class = 80
12  class = 75
13  class = 60
```

Figure 9. Decision tree

4.4 Various plots on using TCSC at firing angle of 75 degree in the capacitive mode

Figure 10. shows the plot for variation in power ,impedance and firing angle of TCSC. There is a change in values after 0.5 seconds as the TCSC is bypassed for the first 0.5 seconds. The simulation is shown for time duration of 1 second[13].The power transfer using TCSC is 380.39 MW at firing angle 75 degree. Figure 11 shows the variation of TCR current and TCSC voltage and figure 12 shows the variation of capacitor voltage and capacitor current.

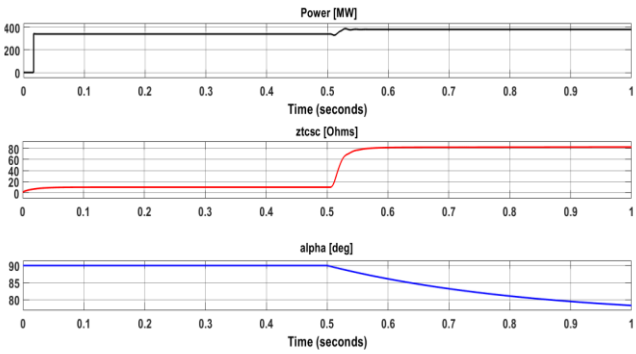

Figure 10. Variation of active power, TCSC Impedance and angle at firing angle of 75 degree.

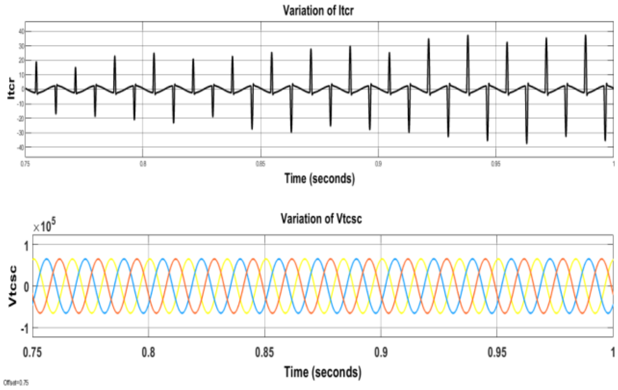

Figure 11. Variation of Itcr, Vtcsc at firing angle of 75 degree in capacitive mode of TCSC

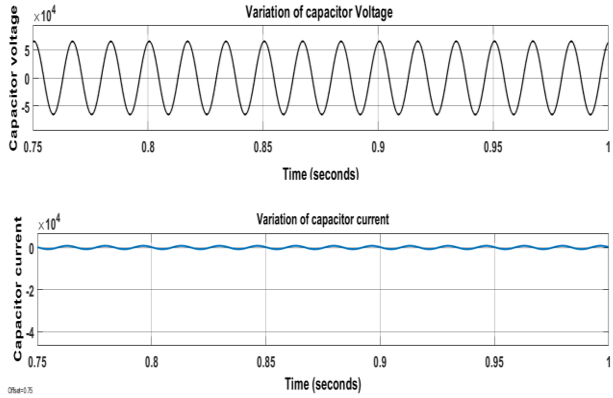

Figure 12. Variation of Capacitor voltage, capacitor current at firing angle of 75 degree in capacitive mode of TCSC

4.5 Various plots on using FC and TCSC at firing angle 75 degree

There is increase in power transfer due to inclusion of FC with TCSC in the system. Various plots are shown for power, angle and impedance of TCSC . With both the devices the power is now 389.73 MW and with TCSC alone the power was 380.39 MW at this firing angle. With FC and using two modules of TCSC both at 75 degree of firing angle the power is found to be 392.55 MW. The other plots of current in TCR, TCSC voltage, capacitor voltage and current also are shown in figures 14,15.

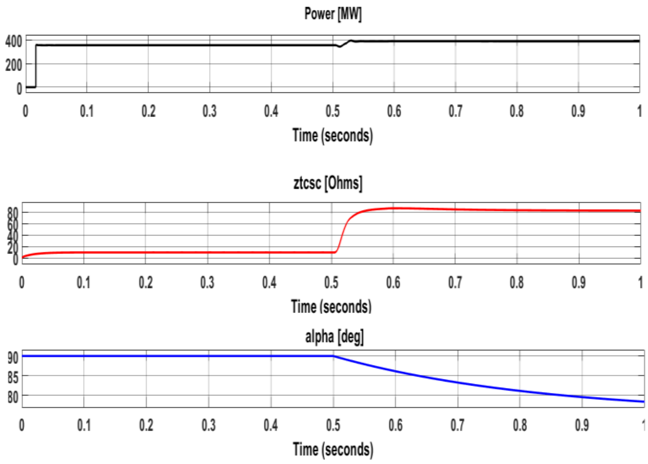

Figure 13.Variation of active power, TCSC Impedance and angle with FC and firing angle of 75 degree in capacitive mode of TCSC

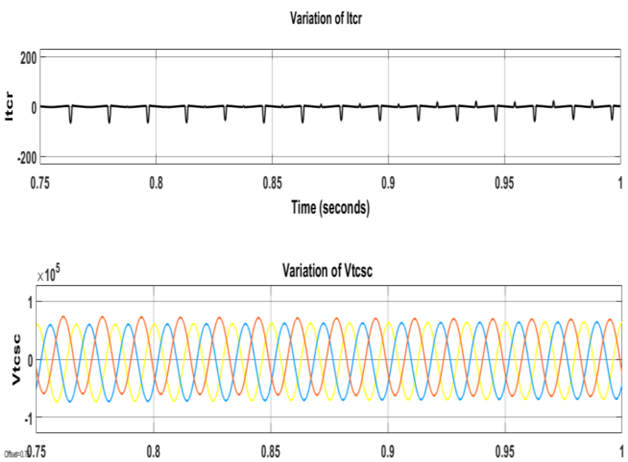

Figure 14. Variation of Itcr, Vtcsc with FC and at firing angle of 75 degree in capacitive mode of TCSC

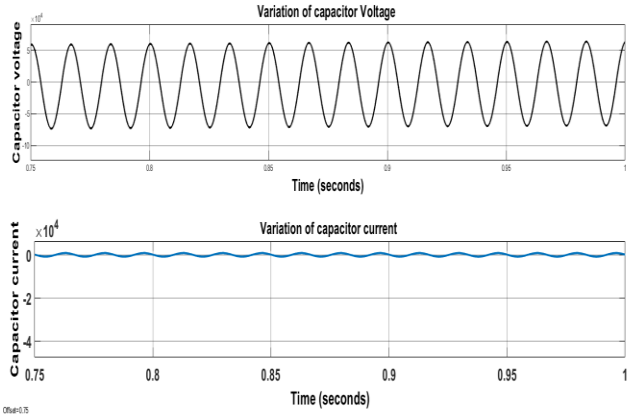

Figure 15. Variation of Capacitor voltage, capacitor current with FC and at firing angle of 75 degree in capacitive mode of TCSC.

4.6 Firing angle prediction in Inductive mode of TCSC using RFMLA

The data of input power and angle is loaded into the system using the command load mydata. The commands from the bagged ensemble program generic_random_forests (X',Y',60,'classification'), predict (BaggedEnsemble, [360]) is used to predict the firing angle which comes out to be 30 degrees for this value of random power input belonging to inductive region of TCSC. The Classification tree viewer generated from MATLAB using RFMLA is

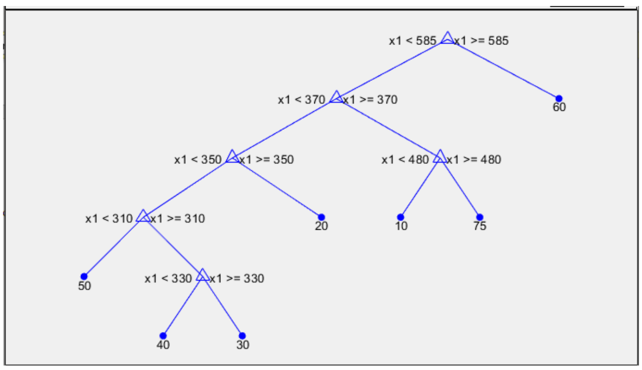

Figure 16. Decision tree Case 2

The classnames are created for all the firing angles from 0 to 90 degrees in step of 10 degrees

The following decision tree is created by MATLAB for the inductive mode of TCSC.The input power is compared with different power and finally the angle predicted is 30 degrees [15].

```
Decision tree for classification
 1  if x1<585 then node 2 elseif x1>=585 then node 3 else 60
 2  if x1<370 then node 4 elseif x1>=370 then node 5 else 10
 3  class = 60
 4  if x1<350 then node 6 elseif x1>=350 then node 7 else 20
 5  if x1<480 then node 8 elseif x1>=480 then node 9 else 10
 6  if x1<310 then node 10 elseif x1>=310 then node 11 else 30
 7  class = 20
 8  class = 10
 9  class = 75
10  class = 50
11  if x1<330 then node 12 elseif x1>=330 then node 13 else 30
12  class = 40
13  class = 30
```

Figure 17. Decision tree Case 2

4.7 Various plots on using TCSC in the inductive mode at firing angle of 30 degree

Again, the various figures are captured for this mode of TCSC with firing angle 30 degrees.

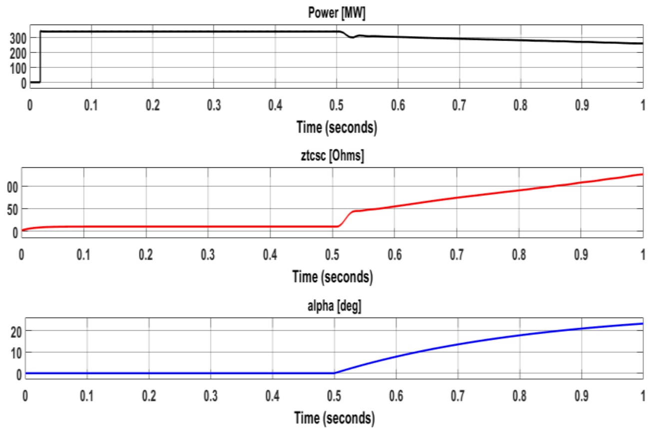

Figure 18. Variation of active power, TCSC Impedance and angle at 30 degree

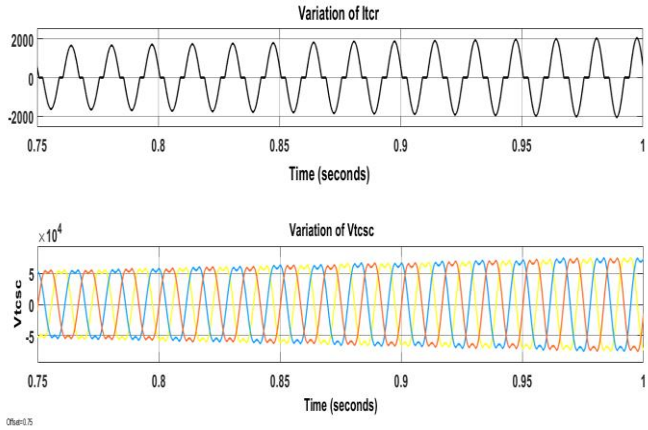

Figure 19. Variation of Itcr, Vtcsc at 30 degree

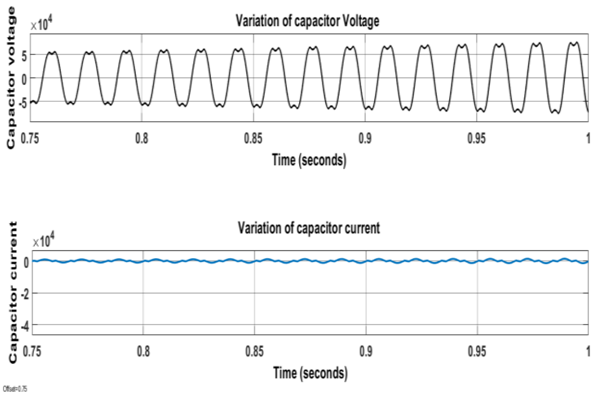

Figure 20. Variation of Capacitor voltage, capacitor current at 30 degree

4.8 Various plots on using FC and TCSC at firing angle of 30 degree

Now FC is used in the system with TCSC at firing angle 30 which lies in the inductive range of this TCSC. Due to FC the power transfer is increased than using TCSC alone. With only TCSC the power is 209.75 MW and with FC and TCSC the power is 225.07 MW. The figures 21,22, 23 show the variation of various parameters at this angle. With using FC and two modules of TCSC at firing angle of 30 degree each the power transfer is 262.22 MW.

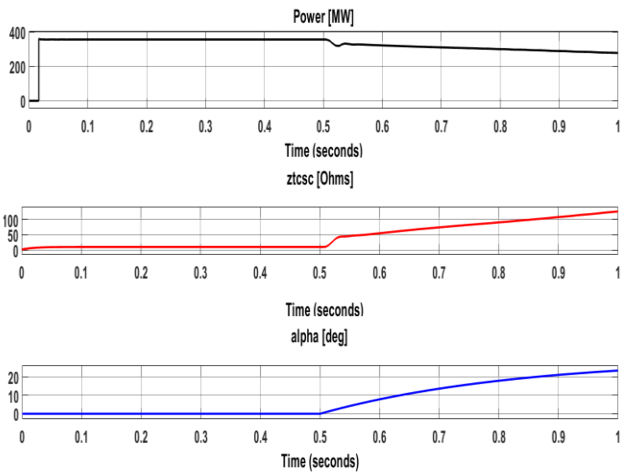

Figure 21. Variation of active power, TCSC Impedance and angle using FC and TCSC at firing angle of 30 degree

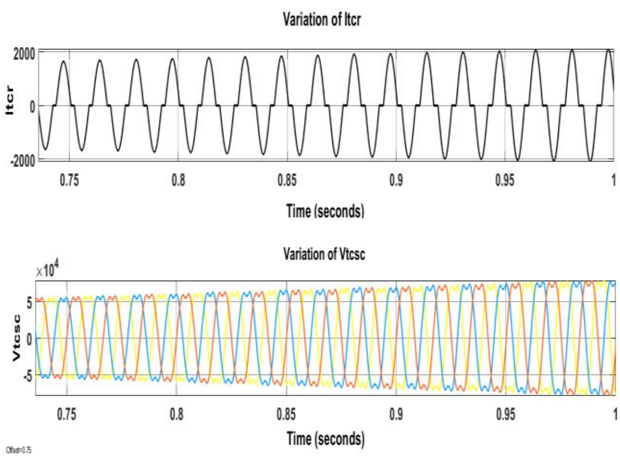

Figure 22. Variation of Itcr, Vtcsc using FC and TCSC at firing angle of 30 degree

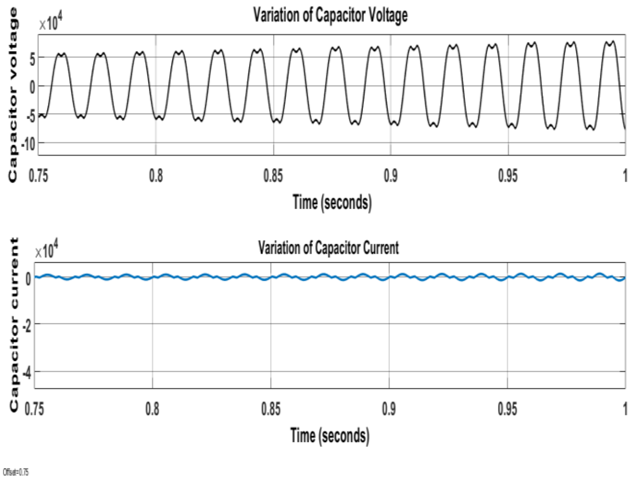

Figure 23. Variation of Capacitor voltage and Capacitor Current using FC and TCSC at firing angle of 30 degree

4.9 THD Analysis

The Powergui from MATLAB is used for THD analysis in the present work. Due to increase in number of nonlinear loads in industries power quality problems associated with distortion in voltage, current and frequency waveform are created. THD studies are very important to find out the voltage and current distortion due to varying nonlinear loads in transmission and distribution system. The low value of THD is desired which means higher power factor, lower peak currents, and higher efficiency of the system. The electronic devices such as PLCs and adjustable speed drives are sensitive to disturbances and faults. TCSC is used to mitigate different power quality problems like voltage sag and voltage swell along with improving power transfer capacity and stability of the system. As shown in table 2 below that using TCSC the THD voltage is improved as compared to uncompensated case.(line only).The simulation is done using TCSC alone and combination of FC with TCSC, FC with two modules of TCSC with different firing angles and harmonic results are shown in table 2.The different values of firing angles in inductive and capacitive range are taken.

Table.2 THD Analysis

S. No	Model. No	Controller	THD Voltage (%)
1.	M1	Line only	0.15
2.	M2	With Fixed Capacitor (FC)	0.15
3	M3	With TCSC at firing angle of 75 degree	0.14
4	M4	With FC and TCSC at firing angle of 75 degree	0.14
5	M5	With FC and two modules of TCSC at firing angle of 75 degree	0.15
6	M6	With TCSC at firing angle 30 degree	4.92
7	M7	With FC and TCSC at firing angle 30 degree	4.19
8	M8	With FC and two modules of TCSC at firing angle 30	8.24

4.10 Total Harmonic distortion from different devices/Controllers

Figures 24 to 31 shows the THD values generated from MATLAB Powergui tool. The results are shown in table 2. The THD is increased in inductive range of TCSC but decreased in capacitve range of TCSC.

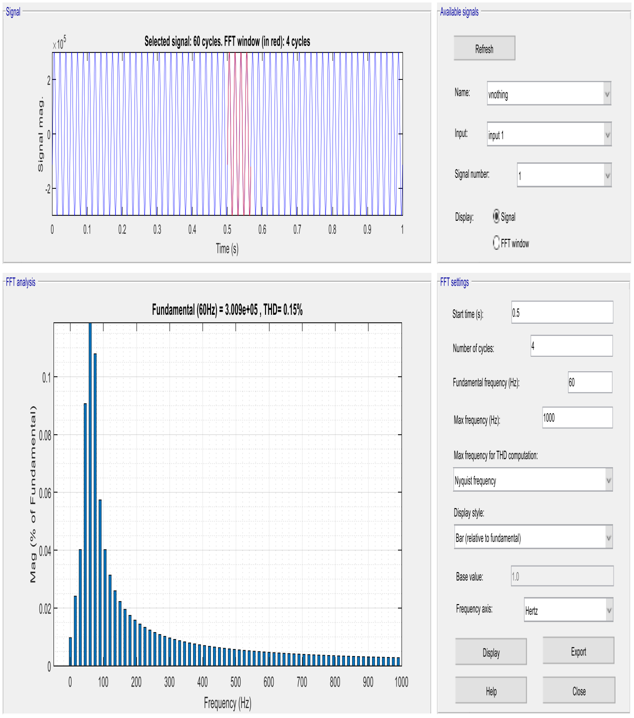

Figure 24 . for M1

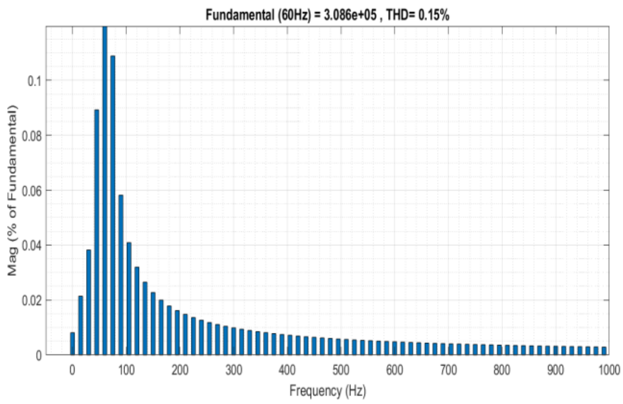

Figure 25.for M2

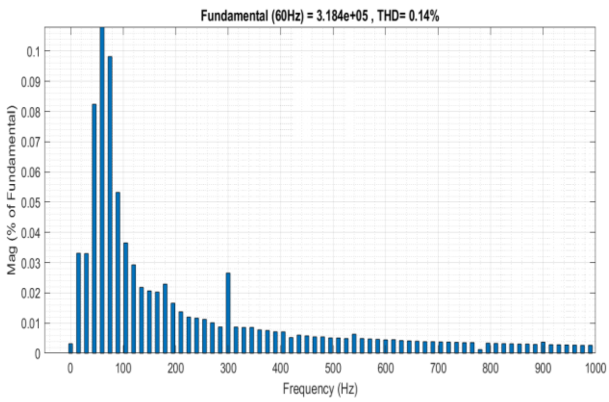

Figure 26.for M3

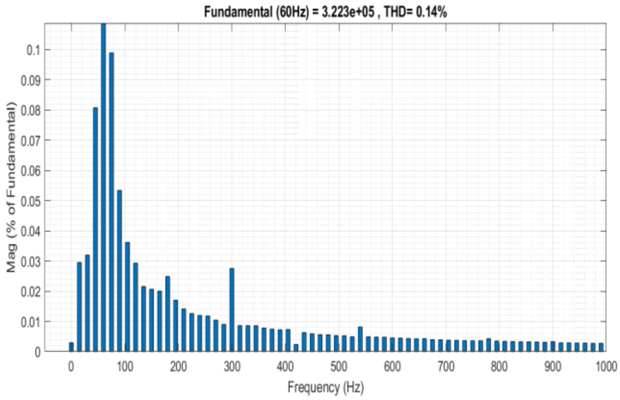

Figure 27 for M4

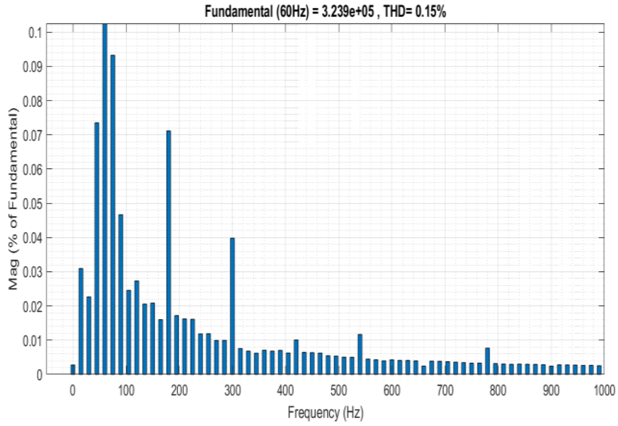

Figure 28. for M5.

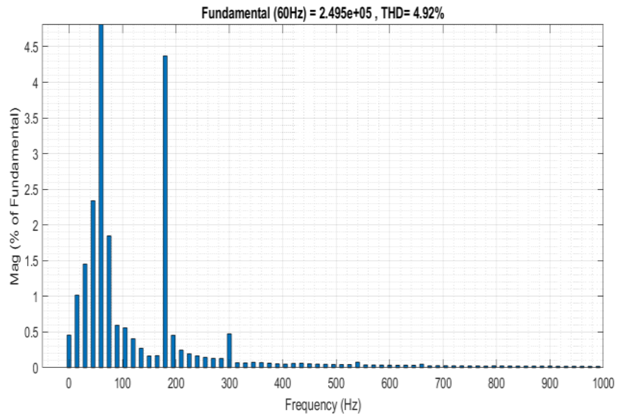

Figure 29.for M6

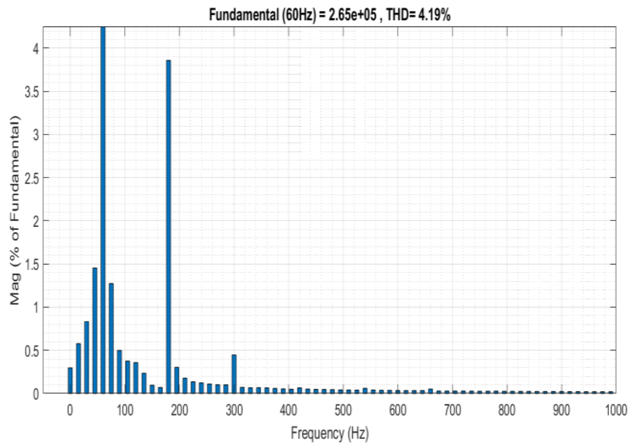

Figure 30 for M7

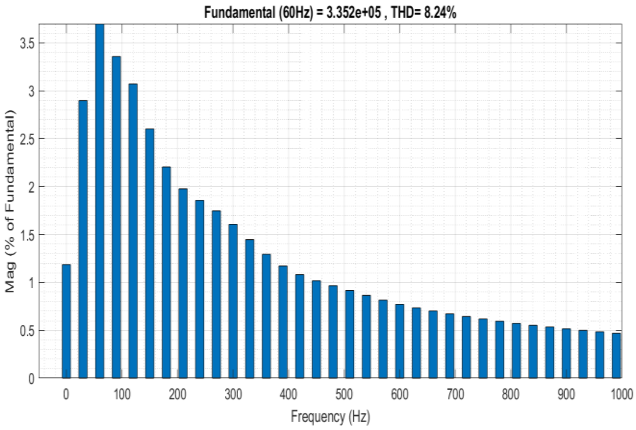

Figure 31.for M8

V. Conclusion and Future Scope

In the present work the desired firing angle for the different modes of TCSC is predicted/determined by machine learning algorithm called Random Forest based on the trained data of input power and firing angle that is loaded into the system. The algorithm creates many decision trees based on the input power and the firing angle .The final value of firing angle is chosen from majority of the votes. There is accurate prediction of firing angle corresponding to the input power as the random forest can handle huge datasets effectively. There is higher level of accuracy in predicting by random forest than decision trees. The work also showed the waveforms with both the modes of TCSC. Then in the next part the THD analysis is done based on FFT from Powergui in MATLAB. The THD values are compared for FC and TCSC with different combinations. The TCSC can be used as fault current limiter to mitigate the power quality problem like voltage sag created due to faults and disturbances. This work can be extended to multimachine bus system The different optimization algorithms can be applied for tuning the PI controllers in TCSC . The TCSC can be analysed with different values of L and C to understand the behaviour of characteristic curve.

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