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Examining the Thyristor-Controlled Reactor's (TCR) Performance to minimize Self-Generated Harmonics.

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Abstract: - This work discusses the minimizing of self-generated harmonics in a Thyristor Controlled Reactor (TCR) used in a power distribution system. When a nonlinear load is connected to the system, power quality difficulties arise, including reactive power compensation, harmonics, voltage unbalance, poor power factor, and so on. These flaws degrade the power quality of the system. FACTS and electronics devices are most commonly employed for reactive power correction. A conventional Static VAR compensator is the best option for this application. The static VAR compensator consists of either a fixed capacitor-thyristor controlled reactor (FC-TCR) or a thyristor switched capacitor-thyristor controlled reactor (TSC-TCR). The reactive power demand objective can be met by controlling the conduction angle of TCR. However, the switching operation of the thyristor-controlled reactor reduces power quality by adding self-generated harmonics into the system. The proposed topology in this study outlines the usage of a delta-connected TCR to reduce self-generated harmonics rather than a thyristor controlled reactor (SCR).
The work carried out in this paper has two major sections
1. Determine (a) the firing angle range for reactive power adjustment, and (b) the mechanism to control inductive susceptibility. 2. A comparison of three presented methods: a) single delta connected TCR; b) Equally stepped delta connected TCR (ESTCR); and c) Binary stepped delta connected TCR (BTCR).

Keywords: Static VAR Compensator (SVC), Thyristor Controlled Reactor(TCR), Equally stepped delta connected TCR(ESDCTCR), Binary stepped Thyristor Controlled Reactor(BTCR).

I. INTRODUCTION

The power distribution system supplies the power to various commercial or nonlinear applications. These types of loads generate or absorb large reactive power in the system. Examples of nonlinear applications would be; machinery used in steel industries and rolling mills, traction motors, furnaces etc. These nonlinear loads introduce unbalance on the power system. Due to this unbalance, undesirable effects appearing in the system would be distortion, flicker etc. To reduce these effects and also to get load compensation, it is necessary to connect compensators in the system. Obviously, compensators should be adaptable to changes in load.

Static VAR compensators (SVCs) are used to compensate for reactive power while also improving power quality. The SVC's can be connected in series or in shunt manner. The shunt compensators serve the same principle of compensation of reactive power by generation or absorption. Types of static VAR compensators use different circuits with thyristor and power conversion [1] [2]. A VAR Compensator (static) either combines TCR with fixed capacitor, or Thyristor Switched Capacitor (TSC). For compensation of reactive power and phase

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wise balanced load demand, appropriate range of conduction angle of thyristor-controlled reactor can be used. Due to switching operation of TCR, self-generate harmonics get harmonics get injected in the power system. To reduce the adverse effects on power quality, it is therefore very essential to minimize the self-generated harmonics. There are various external methods to minimize these harmonics. However, in this topology the internal techniques of minimization are provided. [3] [4].

1. Presented Techniques

The primary goal of this work is to investigate self-generated harmonics in TCR. Firing angle control is used to analyze the relationship between α (defined below) and inductive susceptance. A performance study of delta connected TCR is carried out. The minimization of harmonics created in TCR has been discussed using the following combinations.

1. Use equal TCR steps and control one branch at a time.

2. Using TCR in binary sequence.

The simulation software used is MATLAB.

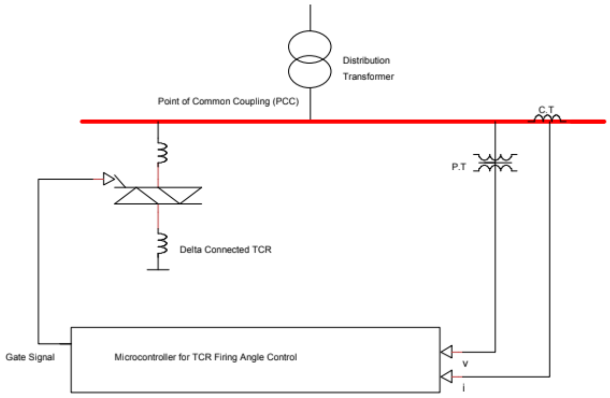


Figure.1 Delta connected TCR Schematic

Figure 1 depicts the fundamental block diagram of the proposed delta-connected TCR system. Delta-connected TCR is used as a compensator. Reactive power is linked to the PCC line.

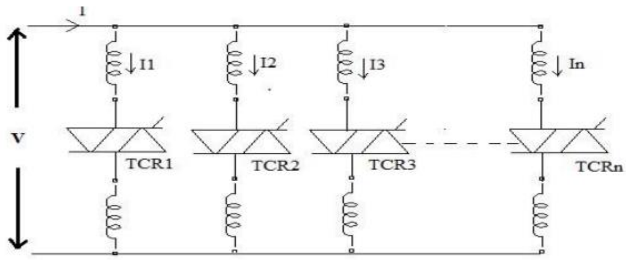


Figure 2 Schematic of ESDCTCR

Figure 2 depicts the evenly divided Delta linked TCR. This approach is suitable for high-power applications. The number of stages is divided based on the required reactive power. The total number of steps are "m" (m≥2) TCRs. The rating for each step is (1/m) * (the needed total rating). Reactors are controlled sequentially. According to the reactive power need, one of the "m" reactors is delay regulated, while the remaining (m-1) reactors are either entirely "on" or "off" [19] [29]. The suggested architecture has a total reactive power consumption of 36 kVAR. As a result, TCR is divided into three equal phases with ratings of 12 kVAR each. The resistance is 1Ω, and the inductive reactance is 74.59 mH.

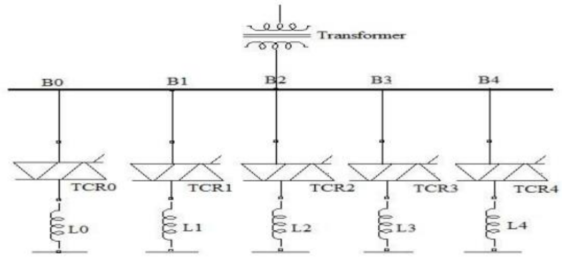


Figure .3 Schematic of TCRBS (Thyristor controlled reactor in binary sequence)

Delta TCR is a binary sequential combination of "n" steps. The number of steps is obtained using the needed power Q in binary sequence. Figure 3 depicts the TCR circuit in binary sequence. In this kind, four reactor bank stages are employed with values of 2.5 kVAR, 5 kVAR, 10 kVAR, and 20 kVAR, totaling 36 kVAR. Binary sequences produce low resolution [2] [9]. The binary sequential reactive power values are shown below.

Q = 2nL + 2n−1L +........ + 22L + 21L + 20L.

The reactor values for each stage are as follows:

For 2.5 kVAR, R = 1Ω and L = 350 mH.

For 5 kVAR, R = 1Ω and L = 170 mH.

For 10 kVAR, R = 1Ω and L = 85.51 mH.

For twenty kVAR,

1. MATLAB Simulation and Discussion

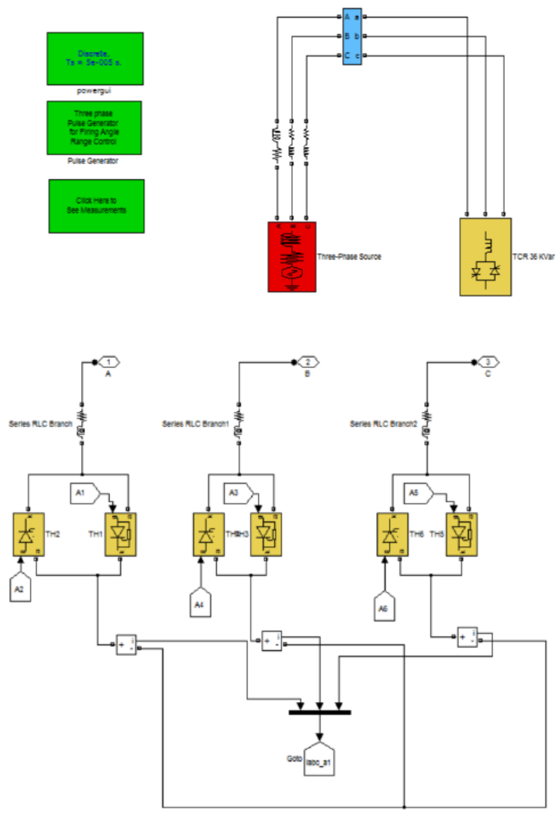


Figure 4 A) MATLAB Model of TCR and

B) 36 kVAR TCR Sub circuit

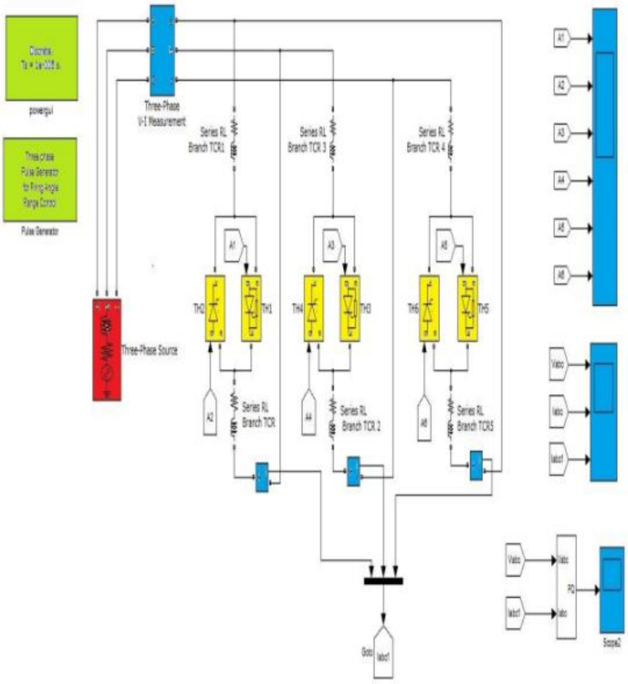


Figure 5 MATLAB Simulation of Delta connected TCR

Figure 4A depicts a three-phase TCR simulation model, whereas 4B depicts its subsystem. Figure 5 depicts an open loop simulation of a three-phase delta-connected TCR. The model contains two RL branches in each phase, each with values of 1 Ω and 25.4 mH. Other components employed include a pulse generator for delivering 440 volts, switches, scopes, measuring blocks, and so on. The primary goal is to investigate the harmonics produced by TCR. This model is used to operate the TCR by determining the firing angle range of 72 to 172 degrees.

Fig 5 shows the fundamental circuit outlines of a three stage delta associated TCR. Delta TCR has bidirectional TCRs in series with reactor. However, here the reactor in each stage is partitioned in two half parts for counteraction of complete AC voltage to be available over the thyristor as displayed in Fig.5. All line and stage waveforms should be visible in scope in the recreation. Number of readings are taken for various terminating points α = 90°, 99°, 108°, 117°, 126°, 135° and so on. For the presentation investigation of TCR, different boundaries are noted from recreation results. They are-50Hz current, DC current part and harmonic current part from second to twelve harmonic and further more dynamic and receptive power. Table 1 shows the different rms values and % of THD w.r.t 50Hz component for firing angle range α = 70° to 135°. The variety of the multitude of current and consonant parts based on terminating point α is displayed in plot of Fig. 6 to Fig.19

II. OBSERVATIONS AND DISCUSSION

(Table 1): **Performance table of DCTCR with variation in α (L: Line value, Ph: phase value)**

Sr.No.	Firing Angle in (°) (α)	% THD		Fund Current component		DC Component		% Harm2	
		L	Ph	L	Ph	L	Ph	L	Ph
1	72	6.42	6.21	43.64	26.0	6.2	2.638	4.80	3.93
2	78	6.63	6.52	43.34	25.88	4.361	1.668	5.05	4.33
3	84	6.81	7.05	42.023	24.91	3.07	0.985	5.21	4.6
4	90	7.86	10.5	36.6	21.94	2.724	0.8902	5.35	4.61
5	96	9.59	15.75	31.58	18.95	2.333	0.755	5.49	4.66
6	102	10.92	21.87	27.02	16.02	1.994	0.6295	5.62	4.7
7	108	11.35	27.64	22.63	13.6	1.654	0.528	5.77	4.74
8	114	10.51	35	18.21	10.95	1.32	0.4211	5.92	4.8
9	120	10.1	43.15	14.47	8.539	1.043	0.3252	6.06	4.85
10	126	12.48	50.91	11.12	6.689	0.7844	0.253	6.13	4.9
11	132	17.94	61.17	8	4.813	0.5571	0.1811	6.2	4.97
12	138	26.51	73.24	5.581	3.262	0.3897	0.1225	6.32	5.04
13	144	40.57	85.71	3.643	2.196	0.2502	0.0826	6.26	5.12
14	150	62.45	104.31	2.07	1.25	0.1425	0.04757	6.27	5.24
15	156	87.37	131.4	1.054	0.6031	0.07551	0.02363	6.58	5.46
16	162	127.45	172.68	0.4162	0.2551	0.03134	0.01075	6.66	5.92
17	168	310.11	377.37	0.06441	0.04187	0.008027	0.002822	10.63	9.53
18	174	73.01	76.7	0.04695	0.02819	0.00084	0.0002149	1.68	1.08

% Harm3		% Harm4		% Harm5		% Harm6		% Harm7		% Harm8	
L	Ph	L	Ph	L	Ph	L	Ph	L	Ph	L	Ph
2.34	3.02	1.8	2.11	1.44	1.37	0.85	0.92	0.91	0.88	0.86	0.91
2.38	3.19	1.94	2.06	1.34	1.22	0.88	0.96	1.02	1	0.83	0.94
2.56	3.75	1.98	2.05	0.75	0.93	0.93	1.01	1.27	1.42	0.82	0.95
2.4	7.34	2	2.26	2.33	2.85	0.82	0.96	2.79	3.03	0.86	1.01
2.58	10.15	2.01	2.38	3.76	4.41	0.8	0.96	3.52	3.84	0.87	1.02
2.48	15.16	1.98	2.58	6.26	6.65	0.81	1	4.14	4.43	0.9	1.02
2.56	21.95	1.92	2.83	8.03	8.43	0.93	1.14	3.28	3.66	0.87	0.98
2.63	29.6	1.8	3.09	8.08	8.6	1.12	1.38	0.85	1.24	0.8	0.9
2.77	36.72	1.59	3.33	6.15	6.98	1.34	1.66	3.14	2.68	0.66	0.86
2.93	45.51	1.25	3.61	1.86	3.4	1.53	2.05	7.27	6.71	0.47	0.95
2.53	54.61	0.77	3.89	7.1	7.4	1.61	2.5	9.52	8.98	0.37	1.26
3.33	62.48	0.26	4.13	17.66	16.64	1.75	2.93	8.17	7.72	0.46	1.69
3.63	71.55	0.55	4.42	31.84	30.49	2.33	3.44	1.5	2.8	0.99	2.33
4.29	84.24	2.06	4.84	55.76	54.18	4.21	4.21	22.44	23.17	2.62	3.41
5.65	98.91	3.25	5.44	83.4	81.65	7.02	5.13	59.24	59.45	5	4.69
4.95	125.45	5.63	6.78	114.7	115.7	10.43	6.66	98.5	101.77	7.36	6.47
4.47	20.82	1.62	1.1	25.83	20.96	2.58	1.13	25.8	21.15	1.77	1.18

% Harm9		% Harm10		% Harm11		% Harm12		Power	
								Active	Reactive
L	Ph	L	Ph	L	Ph	L	Ph	In KW	In KVAR
0.6	0.79	0.68	0.67	0.54	0.53	0.49	0.52	4.239	34.52
0.71	0.75	0.63	0.6	0.53	0.58	0.57	0.59	4.339	34.6
0.64	0.43	0.61	0.61	0.82	0.91	0.59	0.61	4.419	33.71
0.73	1.16	0.65	0.62	1.89	1.83	0.57	0.62	3.869	29.15
0.69	1.68	0.68	0.7	1.73	1.7	0.5	0.58	3.176	25.05
0.79	0.94	0.7	0.82	0.36	0.51	0.43	0.55	3.002	20.96
0.65	1.59	0.66	0.92	1.33	1.45	0.43	0.58	2.526	17.05
0.65	3.7	0.58	0.98	1.54	1.73	0.53	0.72	1.74	13.11
0.54	4.12	0.44	0.96	0.6	1.01	0.6	0.88	0.06538	10.32
0.6	2.06	0.36	0.88	3.46	3.32	0.58	0.97	-0.04033	8.768
0.58	3.44	0.47	0.83	4.04	3.99	0.61	0.94	-0.003757	6.977
0.84	8.38	0.84	1.09	0.79	1.17	0.5	0.81	-0.001582	5.353
1.27	8.77	1.41	1.63	6.48	6.67	0.62	0.92	-0.001155	4.099
1.8	2.53	1.79	2.51	8.64	9.34	1.33	1.65	0.000572	2.814
2.45	22.44	1.49	3.6	2.89	3.76	1.74	2.86	0.001283	1.744
3.29	52.61	0.26	4.81	33.83	31.44	3.43	4.29	0.001585	1.014
10.54	141.33	3.79	9.27	132.65	122.34	12.27	9.07	0.00172	0.3946
4.37	21.35	1.54	1.23	26.35	21.53	2.67	1.29	0.001744	0.03999

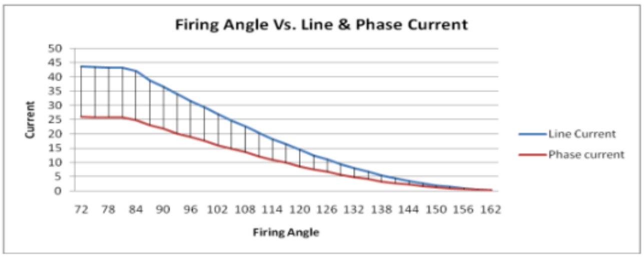
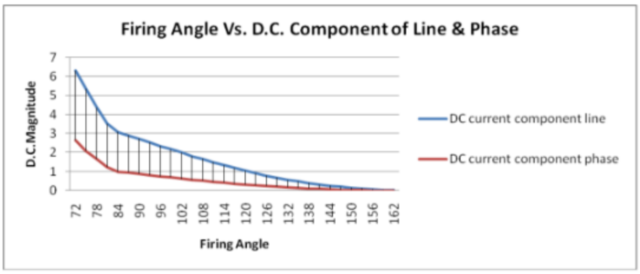


Figure. 6 Change of firing angle on current



(Figure.7) Change of Total current %THD

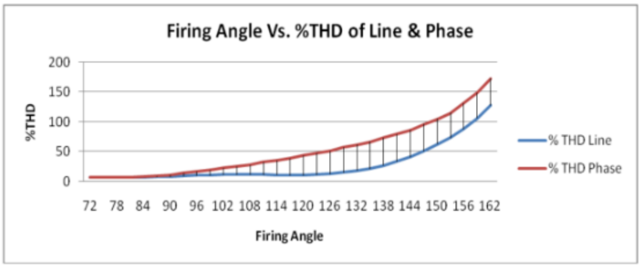
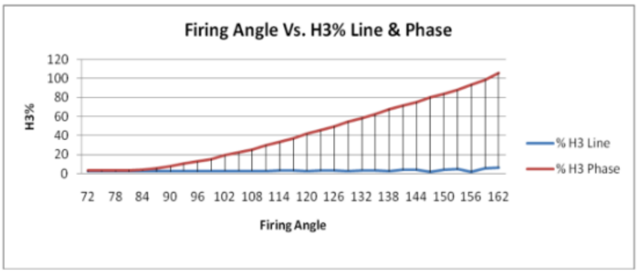
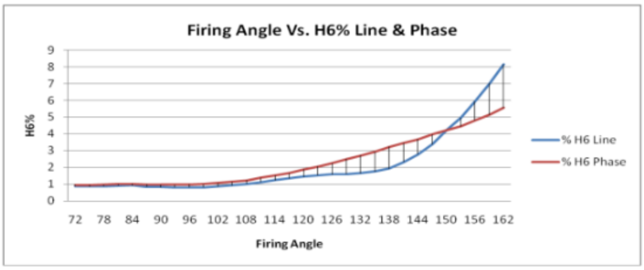


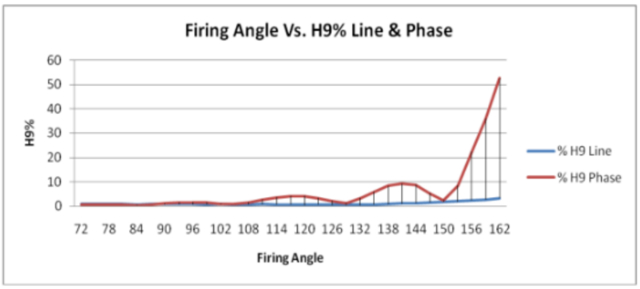
Figure. 8 Change of Total %THD components



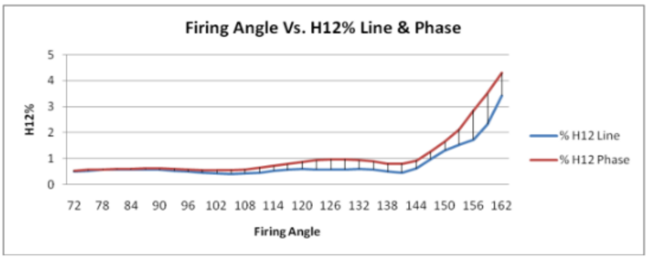
(Figure.9) Change of % Triplen harm.H3



(Figure. 10) Change of %Triplen harm H6



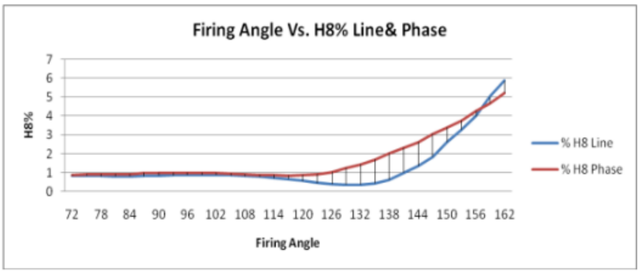
(Figure.11) Change of % Triplen harm H9



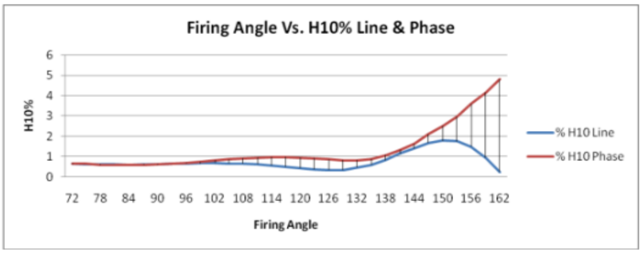
(Figure.12) Change of %Triplen harm H12

(Figure.13) Change of % Even harm H2 Vs firing angle

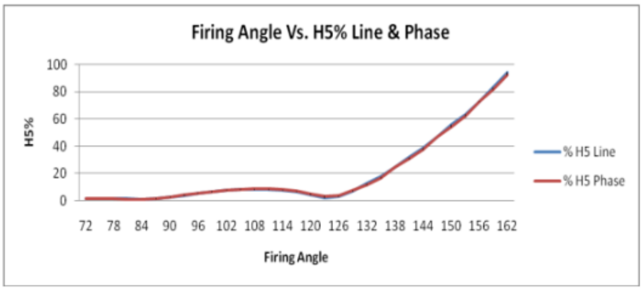
(Figure. 14) Change of % Even harm for H4



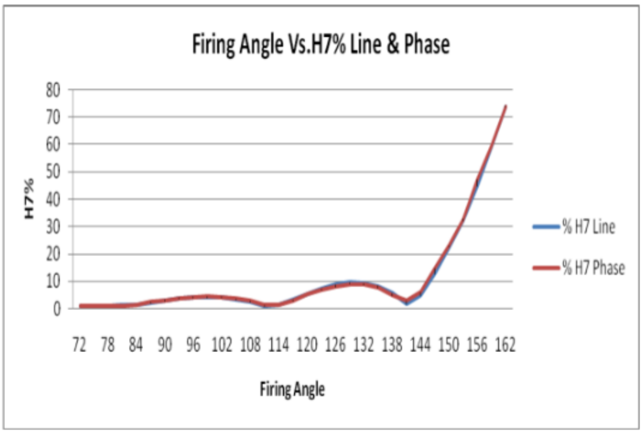
(Figure. 15) Change of % Even harm H8



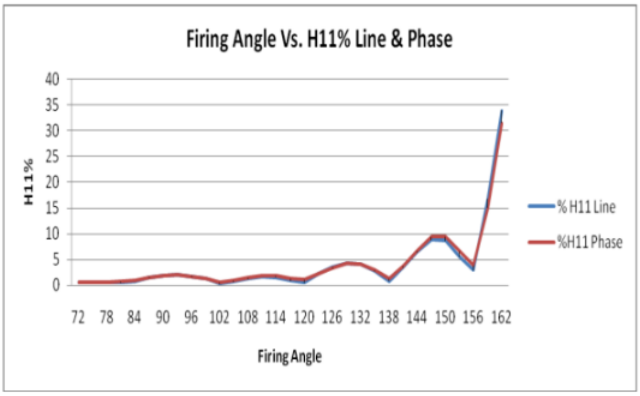
(Figure. 16) Change of % Even harm H10



(Figure.17) Change of %Odd component H5



(Figure. 18) Change of %Odd component H7

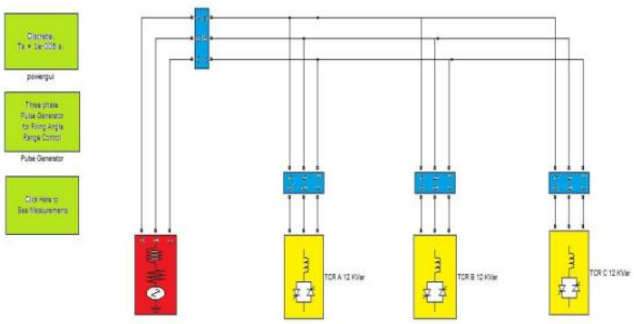


(Figure.19) Change of %Odd component H11

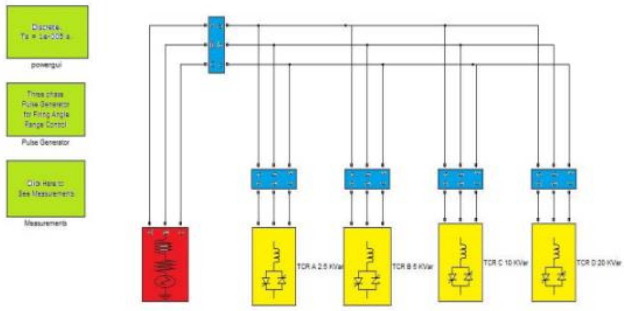
Fig. 6 shows that as the 50Hz current component reduces

with increase in α. Fig.7 shows IL= Iph. DC component decreases when firing angle increased. IL= Iph. Fig. 8 shows THD increases with firing angle increased.

THD increases with firing angle increased. THD increases with firing angle increased. Fig. 9,10,11,12 depicts that, as α rises, all triplet harmonics also rises. For odd triplet, the current component becomes almost zero due to application of DCTCR. Fig.13, 14, 15, 16 shows that 2,4,6,8th harmonics rises with rise in α. Line values are higher than the phase values because of DCTCR. Fig. 17, 18, 19 indicates that all odd harmonics rises with rise in α. Line parameters and phase parameters are same as DCTCR is used.



(Figure.20) MATLAB model for equally stepped DSTCR (Open loop)



(Figure. 21) MATLAB Model for Binary Stepped DCTCR

(Table 2): TCR parameters for different combinations

Combination of TCR	Sr.No.	Reactive power (inKVAR)	Resistance (inΩ)	Inductance (inmH)
Single Delta TCR	1	36	1	25.4
TCR in Equal Stepped method	1	12	1	74.59
	2	12	1	74.59
	3	12	1	74.59
Binary Stepped TCR	1	2.5	1	350
	2	5	1	170
	3	10	1	85.51
	4	20	1	42.75

Table 2 shows the comparison of all the three presented methods. It depicts the effect on % THD and 50Hz component current with variation in α from 70° to 135°.

(Table 3) Simulation Results of three methods

Sr.No	Firing Angle (α)	%THD				Fundamental Current			
		TCR	Delta TCR	Equally Stepped	Binary TCR	TCR	Delta TCR	Equally Stepped	Binary TCR
1	70	8.11	6.38	5.72	5.68	28.2	43.74	45.22	52.43
2	80	8.36	6.68	6.28	6.27	27.95	43.25	44.64	51.76
3	90	8.52	7.86	6.69	6.77	27.69	36.6	43.39	48.82
4	99	8.44	10.28	9.56	9.19	27.36	29.46	33.28	38.75
5	108	8.03	11.35	11.68	11.99	26.75	22.63	25.44	29.06
6	117	9.85	10.05	10.99	11.15	22.74	16.44	18.4	21.27
7	126	12.40	12.48	12.08	11.92	0.08812	11.12	12.34	14.15
8	135	14.67	21.45	20.48	21.80	0.08099	6.826	7.486	8.495

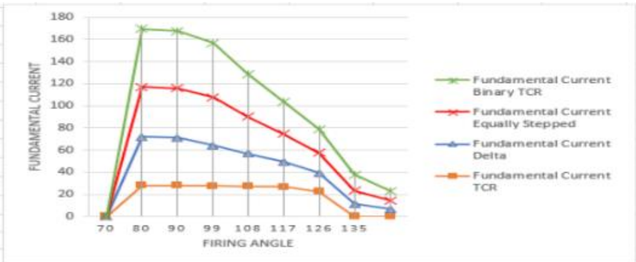
DC Component				%Harm 2				%Harm 3			
TCR	Delta TCR	Equally Splitted	Binary stepped	TCR	Delta TCR	Equally Splitted	Binary stepped	TCR	Delta TCR	Equally Splitted	Binary steppe
0.4277	6.843	15.46	17.73	6.96	4.32	4.43	4.30	2.04	2.35	2.09	2.07
1.303	3.799	8.591	9.886	7.28	5.11	4.84	4.84	1.60	2.39	2.23	2.23
2.123	2.724	3.159	3.511	7.46	5.35	5.25	5.28	1.33	2.4	2.35	2.36
2.213	2.171	2.573	2.956	7.32	5.55	5.51	5.53	1.40	2.48	2.41	2.42
0.5248	1.654	1.932	2.24	6.64	5.77	5.76	5.81	1.54	2.6	2.50	2.52
0.01219	1.185	1.366	1.563	6.50	5.98	5.99	6.00	2.11	2.77	2.64	2.66
0.00267	0.7844	0.8938	1.026	7.23	6.13	6.19	6.23	3.76	3.01	2.84	2.87
0.00254	0.4732	0.533	0.6146	7.50	6.22	6.33	6.43	3.90	3.33	3.08	3.13

%Harm 4				%Harm5				%Harm6			
TCR	Delta TCR	Equally Splitted	Binary steppe	TCR	Delta TCR	Equally Splitted	Binary steppe	TCR	Delta TCR	Equally Splitted	Binary stepped
1.81	1.85	1.63	1.62	1.49	1.48	1.33	1.33	1.04	0.88	0.76	0.76
2.11	1.96	1.82	1.82	1.36	1.30	1.23	1.22	1.05	0.91	0.81	0.81
2.30	1	1.93	1.94	1.22	2.33	0.84	1.33	1.13	0.82	1.00	0.96
2.41	1.98	2.01	2.01	1.26	6.26	5.14	1.29	1.16	0.81	0.72	0.76
2.60	1.87	1.95	1.99	1.66	8.3	8.46	1.16	1.16	1.01	0.78	0.74
2.75	1.59	1.72	1.73	4.95	6.15	7.70	1.13	1.32	1.34	1.17	1.16

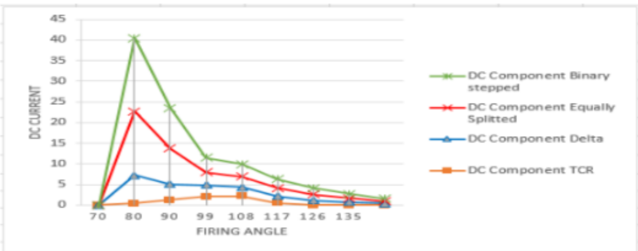
%Harm 7				%Harm 8				%Harm 9			
TCR	Delta TCR	Equally Splitted	Binary stepped	TCR	Delta TCR	Equally Stplitted	Binary stepped	TCR	Delta TCR	Equally Splitted	Binary stepped
0.95	0.89	0.76	0.75	0.91	0.85	0.75	0.74	0.63	0.7	0.61	0.61
1.06	1.04	0.96	0.96	0.77	0.82	0.77	0.76	0.78	0.71	0.66	0.65
1.07	2.79	0.99	1.21	0.72	0.86	0.75	0.77	0.87	0.73	0.70	0.70
0.94	4.14	3.71	3.38	0.89	0.9	0.85	0.84	0.80	0.67	0.69	0.69
0.68	2.34	3.46	3.71	1.01	0.84	0.89	0.88	0.79	0.65	0.66	0.67
2.32	3.14	1.85	1.41	0.87	0.66	0.75	0.79	0.91	0.65	0.63	0.64
10.15	8.61	8.36	8.57	7.41	0.41	0.43	0.48	5.79	0.6	0.56	0.56
10.92	8.17	9.78	11.27	7.68	0.46	0.36	0.33	6.02	0.65	0.63	0.63

%Harm 10				%Harm 11				%Harm 12			
TCR	Delta TCR	Equally Splitted	Binary stepped	TCR	Delta TCR	Equally Splitted	Binary stepped	TCR	Delta TCR	Equally Splitted	Binary stepped
0.73	0.67	0.58	0.58	0.59	0.54	0.48	0.48	0.53	0.49	0.41	0.41
0.69	0.62	0.58	0.58	0.57	0.55	0.49	0.49	0.57	0.58	0.54	0.54
0.58	0.65	0.58	0.59	0.65	1.89	0.72	0.99	0.56	0.57	0.55	0.57
0.68	0.69	0.62	0.62	0.60	1.2	2.10	1.73	0.54	0.46	0.60	0.56
0.84	0.66	0.70	0.67	0.48	1.33	0.98	0.51	0.49	0.43	0.38	0.44
0.79	0.52	0.60	0.61	1.85	0.85	2.14	1.77	0.52	0.57	0.43	0.43
6.79	0.36	0.34	0.40	9.67	3.46	2.62	2.05	4.22	0.58	0.67	0.58
7.05	0.61	0.48	0.48	10.37	2.76	4.56	4.18	4.37	0.59	0.79	0.75

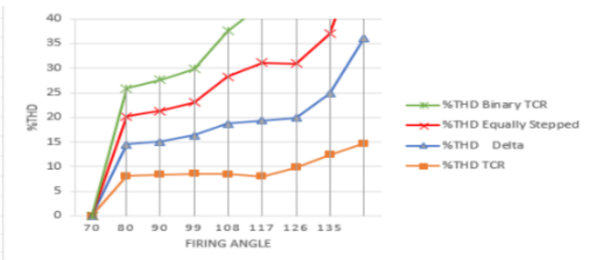
Reactive Power(KVAR)			
TCR	Delta TCR	Equally Stepped	Binary TCR
23.38	34.54	34.05	39.17
23.36	34.61	35.09	40.49
23.33	29.15	35.36	39.61
23.26	23.09	26.58	31.03
23.09	17.05	19.68	22.42
20.26	11.75	13.15	15.23
14.71	8.768	9.241	10.62
14.71	6.261	6.826	7.604



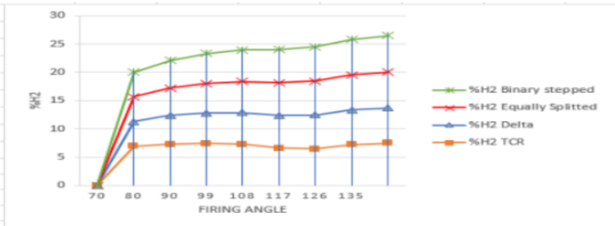
(Figure.22) Current response of TCR to α



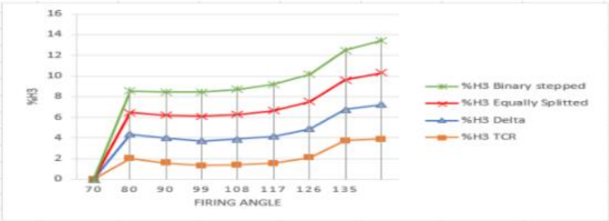
(Figure. 23) DC component current response to α



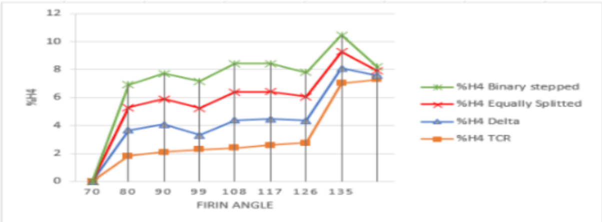
(Figure. 24) % THD response to α



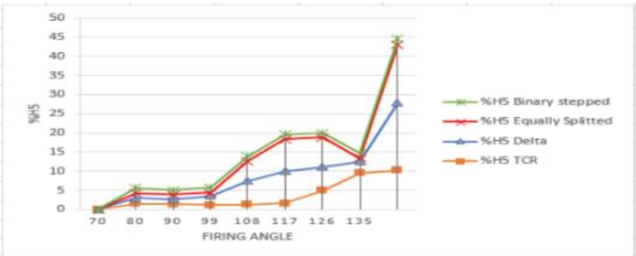
(Figure. 25) Even harmonic component response to α



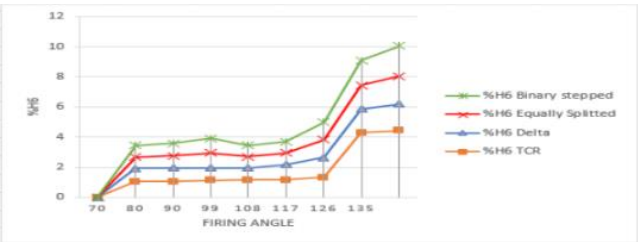
(Figure. 26) Triplen harmonic response to α



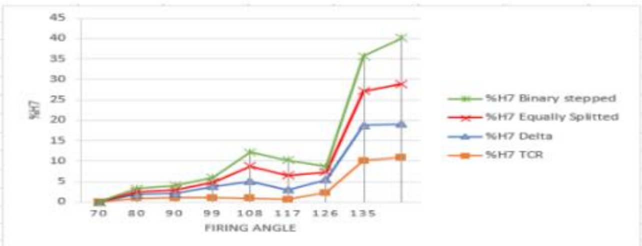
(Figure. 27) Even harmonic response to α



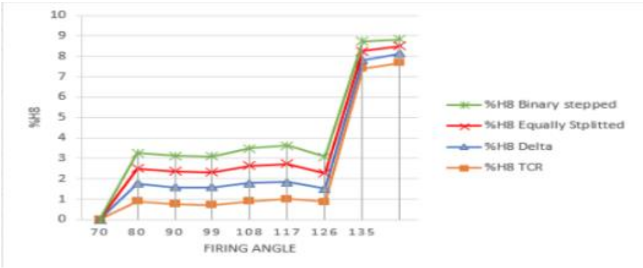
(Figure. 28) Odd harmonic response to α



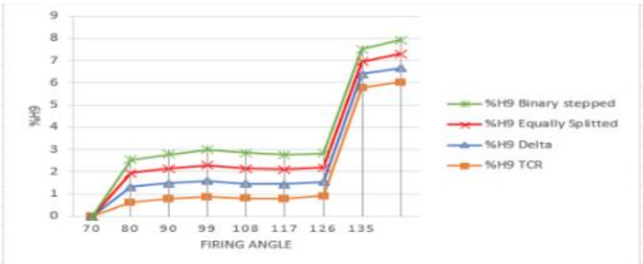
(Figure. 29) Sixth harmonic response to α



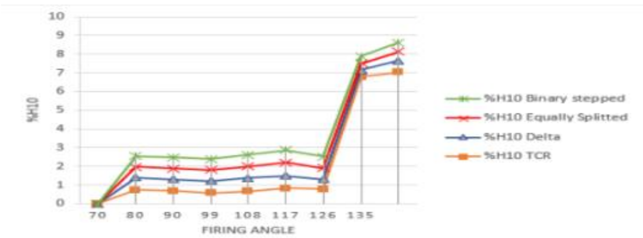
(Figure. 30) Seventh harmonic response to α



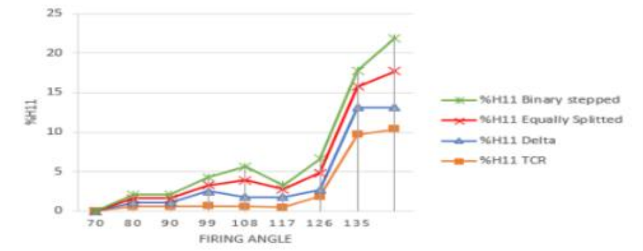
(Figure.31) Eighth harmonic response to α



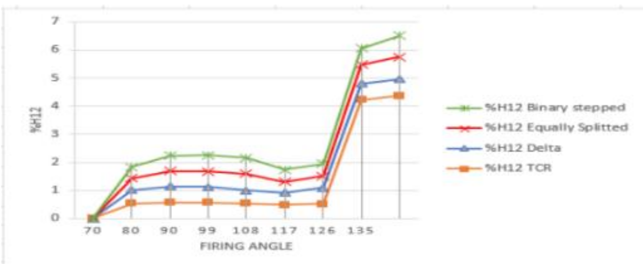
(Figure.32) Ninth harmonic response to α



(Figure.33) Tenth harmonic response to α

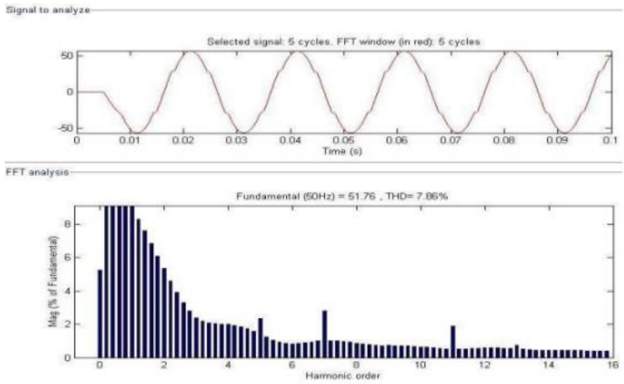


(Figure. 34) Eleventh harmonic response to α

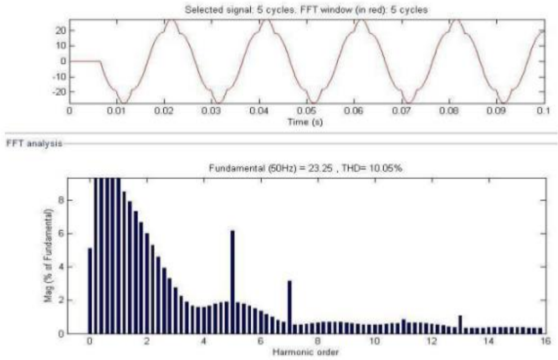


(Figure.35) Twelfth harmonic response to α

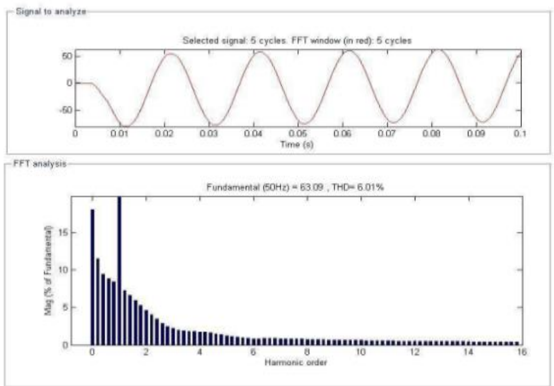
Fig 22 to Fig 35 shows the response of various parameters with change in α for all the three methods. As the α is rising, the 50Hz current & DC current component also reduces for all presented methods namely single delta, equally stepped, binary stepped. Both the current components for BTCR are more and for single TCR are less. If α rises then , all harmonic components also rises. But harmonics present in Single TCR are more than equally stepped and binary BTCR. BTCR gives very less harmonics as compared to that of single delta and equally stepped methods. Hence BTCR is better solution among the all presented methods.



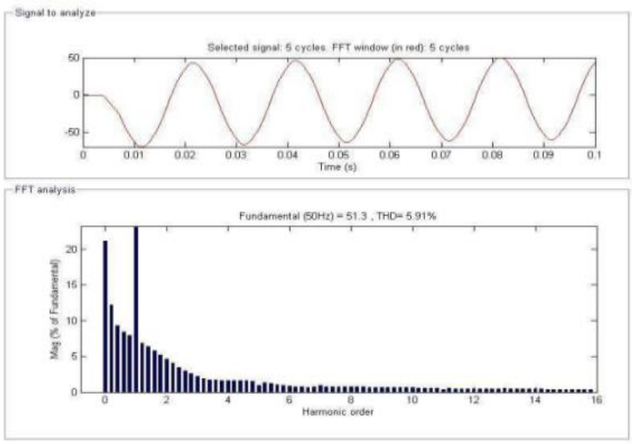
(Figure. 36A) : Line harmonics at α=90° for DTCR



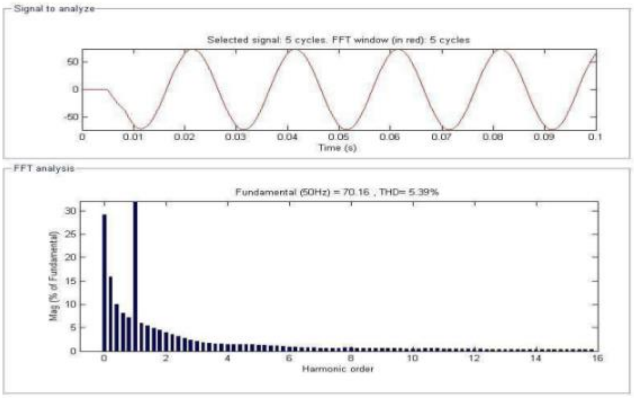
(Figure. 36B) : Line harmonics at α=117° for DTCR



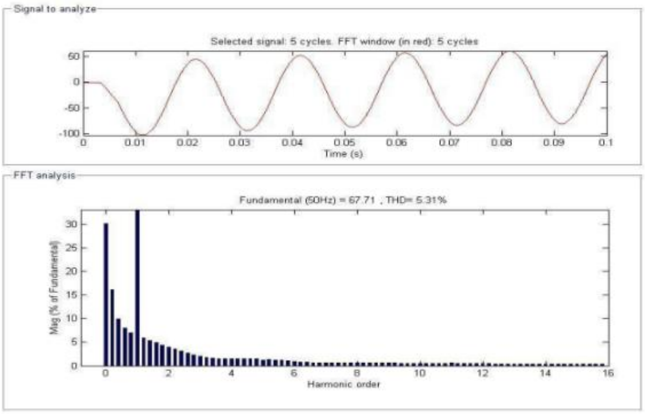
(Figure. 36C) : Line harmonics at α=90° for Equally Stepped DTCR



(Figure. 36 D): Line harmonics α=117° for Equally Stepped DTCR



(Figure. 36E): Line harmonics α=90° for Binary Stepped DTCR



(Figure. 36 F): Line harmonics α=117° for Binary Stepped DTCR

III. CONCLUSION

Thyristor Controlled Reactor (TCR) is a key component of standard SVC for reactive power correction. However, it causes harmonics in the system. The operation of a static var compensator under certain conditions may raise the percentage of harmonic components and imbalanced reactive power, which are detrimental to the system. Delta linked TCR with firing angle range control can be utilized to provide harmonic reduction and reactive power adjustment. This study provides suggested Delta-connected TCR approaches for reducing self-generated harmonics. To reduce self-generated harmonics, two more delta-connected TCR combinations are now employed. These three strategies are also compared to traditional TCR connections. The following are the highlights.

1] The first approach, a three-phase single delta coupled TCR, produces the most harmonics when compared to evenly stepped and binary stepped systems. This strategy reduces only an odd number of harmonics.

2] The second approach, evenly stepped delta linked TCR, decreases harmonics by 35% more than the single delta connected TCR.

3] The third approach, binary sequentially stepped delta linked TCR, decreases harmonics by up to 45% when compared to the single delta method and 25-28% when compared to the evenly stepped delta method.

Furthermore, all three delta-connected TCR combinations produce fewer harmonics than the standard TCR connection. Based on the comparison and analysis of the two approaches mentioned above, the thyristor binary controlled reactor (TBCR) is the best way for decreasing harmonics since it requires fewer steps to operate.

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