actiVAR™ - Performance in Mitigating Voltage Sags Associated with Motor Starting

We are often asked, “How will the actiVAR™ controls and static valves (solid-state switches) respond to large motor starts?”

Describing the response to such a dynamic event is complex; slight differences in events cause different responses. Across-the-line motor starts, however, are sufficiently similar and their response can be generalized with reasonable accuracy.

This tech note provides background and operational results for a 4160V across-the-line motor start application as shown in Figure 1. Situated in a remote location, the system performance requirements were:

1. Successfully start three 600 HP induction motors in close succession.
2. During the motor start event, the voltage at the PCC (point of common coupling) was not to exceed 3.5%. Because of the customer transformer impedance, this requirement translated to a 7.1% voltage sag on the 4160 customer bus.

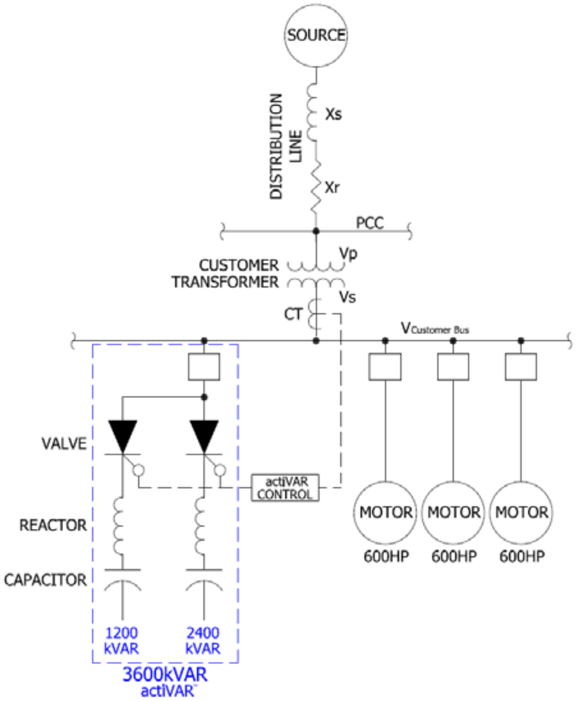

Figure 1 - *Simplified 1-Line Diagram of actiVAR™ System Customer Motor*

Background

Due to the long distribution line and utility voltage sag constraint at the PCC of 3.5%, the customer was forced to put a remedial action plan together to meet their utility flicker demands. Various methods were investigated to determine which solution was most economical and beneficial to the plant. Solutions included:

1. Install a reduce voltage soft starter (RVSS) to reduce the motor current during the actual motor starts. The soft start was only able to reduce the voltage sag by approximately 50%. This was determined to not be enough and was ruled out. Additionally, the customer had multiple 600 HP motors, and therefore one RVSS would have to be purchased for each motor or complex transfer switchgear would be required. This was more costly than purchasing one actiVAR™ for their three 600 HP motors.

2. Install a VFD to control the motors speed and torque by varying the frequency to the motor. The VFD achieved the voltage sag performance objective of 3.5% at the PCC, but would require complex transfer switchgear to start multiple motors. Due to the additional losses associated with the VFD, the lack of a requirement or benefit for speed control of the motor, and the complex transfer switchgear requirements to start three motors, the customer opted for the actiVAR™.

actiVAR™ Recommendation

Based on system analysis, which included a harmonic analysis and dynamic motor start analysis, NEPSI recommended a 3600 kvar actiVAR™ as shown in Figure 4.

The actiVAR™ consisted of an incoming chain drive operated air-disconnect switch, ground switch, and fixed mounted vacuum circuit breaker. The inclusion of these features allowed for direct connection of the system to the customers overhead bus at the transformer secondary. All protection and control of these devices were included in the actiVAR™ design.

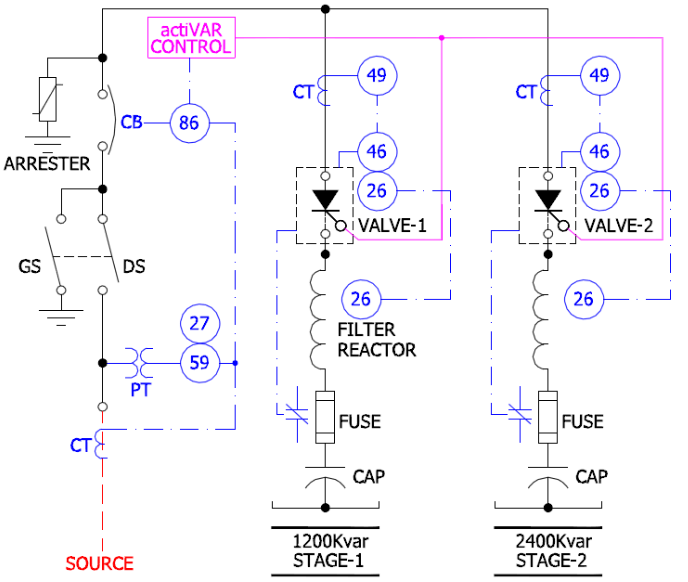

Figure 2 - *Recommended actiVAR™ to Reduce Voltage Sags to 3.5%*

The actiVAR™ consisted of 2 stages allowing for the binary switching of the stages to improve voltage resolution when transitioning off. Binary switching allows for 4 possible switching levels, 0 kvar, 1200 kvar, 2400 kvar, and 3600 kvar.

The actiVAR™ controls the thyristor valves on each phase in the following ways:

1.) It samples line voltage on each phase at 256 samples/cycle and digitizes the waveforms.
2.) It samples one phase of line current (referenced as “phase A”) at 256 samples per cycle and digitizes the waveform.
3.) Using the digitized signals from 1 & 2 above, the actiVAR™ control calculates the load current and phase angle in real time, and determines how many vars to apply to each cycle on each phase.
4.) During the initial (inrush) phase of a motor start, the actiVAR™ control also uses information about the voltage perturbation from all phases to determine how many vars to apply on each phase, once per cycle, 120 degrees apart from the var application on the other phases.

5.) Except for the first cycle, the load is symmetrical. As a result, the above control works extremely well, responding once per cycle per phase. By "transferring knowledge" about a symmetrical load from one phase to the next phase, the actiVAR™ effectively anticipates the requirements for the next cycle.

The actiVAR™ was shipped on a flatbed trailer, fully assembled, tested, and ready for interconnection as shown in *Figure 3*. Figure 3 shows an actiVAR™ being lowered onto a concrete pad. Cables were pulled before the equipment arrived to allow for a quicker installation.

actiVAR™ Performance Results

The performance of the actiVAR™ is shown in Figure 4. The figure shows the first 600 HP motor comes up to speed in approximately 1.75 seconds (plot is shown in cycles based on 60 Hertz). During the motor start the average voltage at the motor terminals is about 0.96 PU. Without the assistance of actiVAR™, average starting voltage (when the motor start is successful) is about 0.82 PU. This is achieved while eliminating any overvoltage conditions longer than one cycle and maintaining phase-to-phase voltage balance while adjusting applied capacitance to meet – or exceed utility flicker requirements.

***Figure 3** - actiVAR™'s are Shipped Fully Assembled and Ready for Interconnection. Enclosures are designed for indoor and outdoor application.*

Figure 4, on a cycle-by-cycle basis, shows the power system voltage, the load current (current to the motor) and the current flowing through the actiVAR™ (right-hand axis).

The motor start occurs near the 4th cycle of the plot and by cycle 110 the motor is operating at full current and full speed and the actiVAR™ current has transitioned off to zero amps.

After the first motor start, the remaining motors may be started in succession. Full system capacity is immediately available for successive motor starts as soon as the actiVAR™ current drops to zero.

Note: *The actiVAR™ can be equipped with integral vacuum-switched power factor correction banks to boost steady-state power factor. Advantages of a combined system are significant but aren't discussed further here.*

Three areas are called out in the plot of Figure 4.

First is the acceptable voltage control zone (yellow shaded area). So long as the voltage during the motor start stays within this range, the voltage sag/PQ and motor start objectives will be met. Because of the stepped nature of the actiVAR™ this is an *engineered result*: by having an understanding of the end objectives, NEPSI suggested a system that achieves the target results at the minimum delivered and installed cost.

Second is the initial inrush. This is the phenomenon that occurs as the motor is initially energized and the system responds. This typically lasts one cycle.

Third is the transition - or stepping off - of the actiVAR™. For much of the motor starts, the voltage actually rises slightly as the motor current and associated var requirement begins to drop (see motor current at bottom). However, the system does not reduce the amount of VARs applied until it has a “better” solution. This switching away from maximum output occurs rapidly at the transition point as the VARs applied are reduced from 3600 kvar to 0 kvar in three uniform reductions of 1200 kvar.

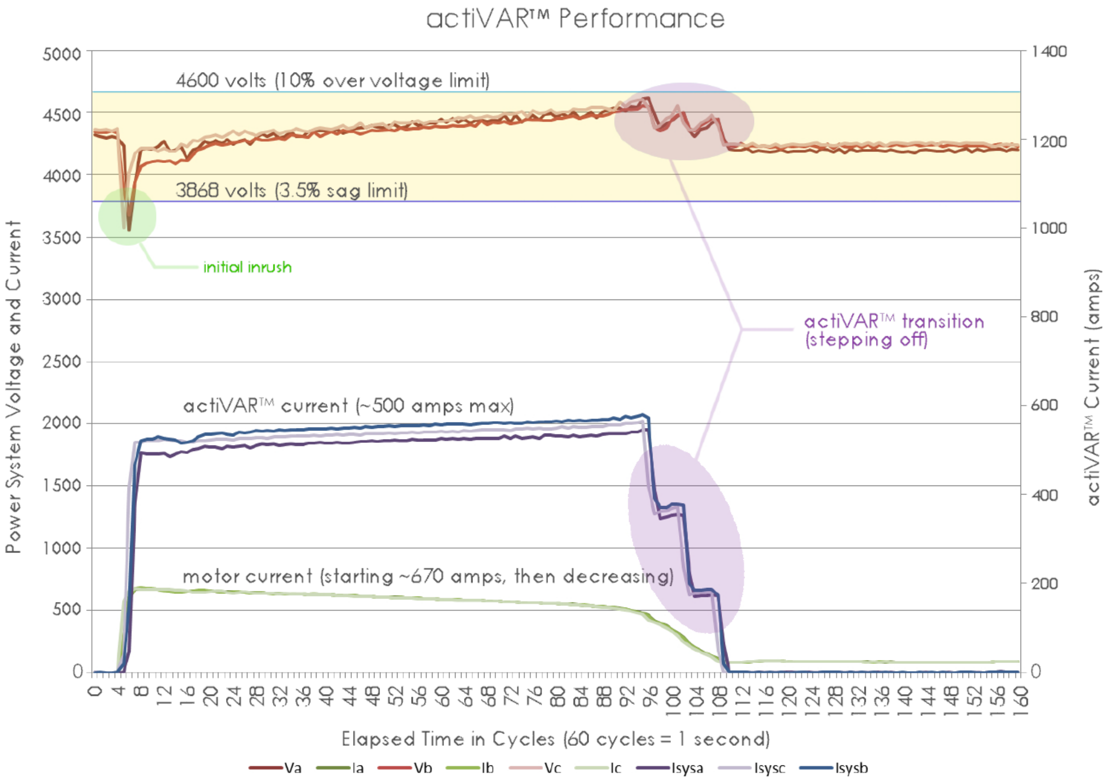

Figure 4 - *actiVAR™ Performance for*
1st 600 HP Motor Start

actiVAR™ - Binary Stage Sizing

Table 1 shows that sizing the stages in a "binary" fashion effectively increases the number of steps the actiVAR can apply to obtain better resolution. Generally speaking, 2-stage (3-step) systems are adequate for simple motor starts, 3-stage (7-step) systems are adequate for complex motor starts and most operations where flicker is a concern. 4-stage (15-step) systems are reserved for complex applications or where current limitations increase the number of switches required.

Table 1 – *Binary Stages*

System Stages	Available steps (binary combinations)	Available non-zero steps
2	4	3
3	8	7
4	16	15

The actiVAR™ controller constantly performs four basic functions:

- It monitors system voltage and load current at speeds commonly seen in PQ monitoring devices to determine the real power (P_{load}) and reactive power (Q_{load}) drawn by each phase of the load in real time.
- The controller constantly calculates how much reactive power (Q_{sys}) must be inserted into each phase to cancel the real and reactive load (P_{load} and Ql_{oad}), choosing the combination of stages that best meets these requirements.
- On each cycle, as each phase approaches the negative peak voltage, the controller operates ("fires") the best possible combination of stages.
- The controller then checks to verify that the stages fired actually operate.

actiVAR™ Performance Analysis

From the control description it's easy to see that three categories of sub-optimal performance are possible even with a properly operating controller:

1. ***Speed*** – the load is changing so fast the controller can't respond in a timely manner. This is not an issue with motor starting, but has been encountered in some unusual situations such as sub-cycle welding.
2. ***Too few available VAR levels***. When this occurs, the controller is fast enough, but the stages available are either too limited (simply not enough) or improperly sized ("available system vars" fall too far away from Q_{sys} so often that the voltage sag or flicker goals are not met.) This can be addressed by proper engineering analysis and system design.
3. ***actiVAR™ switching problems.*** The controller is commanding, but the switches aren't responding. This is unusual, and is carefully monitored as a performance and maintenance issue.

Motor Start Detail Examination

Portions of the motor start shown can be examined in more detail using the actiVAR™ controller data logs. An excerpt from the data log is shown in Table 2 for the first 25 Cycles. Time has been indicated in cycles, and data fields not discussed have been omitted.

Initial Inrush

The data log in Table 2 shows no motor current prior to the 5th cycle. Note that in the 5th cycle:

- $I_a<I_b<I_c$ as is the calculated Q_{req} on each phase.
- The controller responds with 2/3^{rds} of total capacity on phase A, and all capacity on Phases B and C
- By the end of the 6th cycle, all phases have all capacity on.
- All feedback indicates that all switches are on.

Despite this rapid response, during the 6th cycle, the voltage drops (for one cycle, rotating C, A, B) to 0.82 PU before recovering to 0.92PU on the 7th cycle and ~0.97+ PU on each of the subsequent cycles.

Comparison of the maximum Q_{req} per phase (near 1900 kvar) with the system capacity per phase (1200 kvar) shows that the maximum var requirement momentarily exceeds the system capacity by 700 kvar/phase during that time. As the motor begins to accelerate, Qreq drops rapidly and the system voltage recovers within a cycle. This was an engineering decision, not a controller speed issue: as the system design performance exceeded customer and utility requirements, increasing system size from 3600 kVAr to > 5,000 kVAr wasn't either necessary or economically beneficial to customers.

Off Transition

The data log in Table 3 Operating Transition shows no change in system output prior to the 96th cycle. Note that in the prior cycles the Qreq per phase is steadily counting down. It's already below the per phase capacity of 1200 kVAR, but well above the next highest output level (800 kVAR). Based upon the level and trend, the controller begins to remove capacitance in the 96th cycle, in phase order (A, B, C). Six cycles later again based on level and trend, it changes from applying 800 kVAR per phase to applying 400 kVAR per phase. Five cycles later, again on level and trend, it removes all capacitance from the system.

The voltage changes caused by removing capacitive steps are again an engineering decision, not a speed issue. As the system design performance exceeded customer and utility requirements for the motor starts, increasing the number of switches per phase from 2 to 3 (moving from 3 capacitive levels to 7) again wasn't either necessary or economically beneficial to customers.

Table 2 – *First 25 Cycle Data Showing actiVAR™ Performance During Initial Motor Inrush*

Cycle count	Va	Pua	Ia	Isysa	Pa	Qa	QreqA	S1ao	S1aa	S2ao	S2aa	Vb	Ib	Isysb	Pb	Qb	QreqB	S1bo	S1ba	S2bo	S2ba	Vc	Ic	Isysc	Pc	Qc	QreqC	S1co	S1ca	S2co	S2ca
0	4324	1	1	2	4	0	-1	0	0	0	0	4345	0	0	1	0	0	0	0	0	0	4368	1	1	2	0	-1	0	0	0	0
1	4308	99.6%	0	0	2	0	0	0	0	0	0	4339	1	1	2	0	-1	0	0	0	0	4362	1	0	2	0	-1	0	0	0	0
2	4298	99.4%	0	0	1	0	0	0	0	0	0	4343	0	0	1	0	0	0	0	0	0	4367	0	0	1	0	0	0	0	0	0
3	4309	99.7%	1	0	2	0	-1	0	0	0	0	4351	1	0	2	0	-1	0	0	0	0	4353	1	0	2	0	-1	0	0	0	0
4	4299	99.4%	0	0	2	0	0	0	0	0	0	4334	1	1	3	0	-1	0	0	0	0	4371	2	1	1	4	8	0	0	0	0
5	4235	97.9%	185	2	270	-334	-456	1	1	0	0	3860	301	20	271	-670	-792	1	0	0	0	3574	574	41	500	-1386	-1612	1	0	1	0
6	3559	82.3%	599	47	582	-1526	-1788	1	1	1	1	3675	612	152	518	-1617	-1849	1	1	1	0	4020	658	415	620	-1639	-1918	1	1	1	1
7	3929	90.9%	670	371	625	-1612	-1892	1	1	1	1	3939	675	467	535	-1615	-1853	1	1	1	1	4167	675	518	654	-1550	-1842	1	1	1	1
8	4206	97.3%	678	495	590	-1542	-1804	1	1	1	1	4068	681	522	513	-1559	-1785	1	1	1	1	4213	668	519	618	-1480	-1754	1	1	1	1
9	4217	97.5%	676	492	582	-1515	-1771	1	1	1	1	4097	678	526	507	-1542	-1763	1	1	1	1	4212	670	521	624	-1478	-1751	1	1	1	1
10	4210	97.4%	672	492	555	-1510	-1752	1	1	1	1	4107	673	526	514	-1527	-1749	1	1	1	1	4217	668	522	617	-1474	-1742	1	1	1	1
11	4229	97.8%	669	491	568	-1495	-1741	1	1	1	1	4114	669	530	518	-1510	-1732	1	1	1	1	4189	667	522	649	-1457	-1738	1	1	1	1
12	4271	98.8%	663	494	575	-1471	-1718	1	1	1	1	4107	658	527	550	-1471	-1706	1	1	1	1	4214	670	525	641	-1460	-1735	1	1	1	1
13	4187	96.8%	659	486	575	-1470	-1715	1	1	1	1	4113	652	526	568	-1456	-1697	1	1	1	1	4188	667	524	674	-1453	-1741	1	1	1	1
14	4202	97.2%	653	491	585	-1453	-1701	1	1	1	1	4089	646	523	561	-1448	-1684	1	1	1	1	4186	665	521	688	-1442	-1734	1	1	1	1
15	4229	97.8%	651	497	583	-1449	-1694	1	1	1	1	4121	646	517	535	-1450	-1672	1	1	1	1	4243	662	521	625	-1446	-1709	1	1	1	1
16	4128	95.5%	651	495	537	-1467	-1689	1	1	1	1	4113	649	519	493	-1479	-1680	1	1	1	1	4229	655	518	632	-1443	-1707	1	1	1	1
17	4199	97.1%	655	503	548	-1466	-1691	1	1	1	1	4161	654	521	462	-1487	-1672	1	1	1	1	4276	645	518	600	-1409	-1656	1	1	1	1
18	4213	97.4%	655	504	538	-1455	-1673	1	1	1	1	4199	660	531	438	-1498	-1670	1	1	1	1	4273	641	521	594	-1394	-1637	1	1	1	1
19	4271	98.8%	656	509	555	-1441	-1665	1	1	1	1	4218	662	536	446	-1491	-1665	1	1	1	1	4300	643	522	588	-1388	-1626	1	1	1	1
20	4252	98.3%	654	507	530	-1441	-1652	1	1	1	1	4241	658	536	464	-1471	-1651	1	1	1	1	4310	653	524	596	-1409	-1649	1	1	1	1
21	4277	98.9%	651	507	517	-1430	-1633	1	1	1	1	4252	649	538	475	-1439	-1623	1	1	1	1	4321	659	525	603	-1415	-1656	1	1	1	1
22	4251	98.3%	645	505	485	-1427	-1613	1	1	1	1	4239	642	539	466	-1428	-1606	1	1	1	1	4301	656	526	612	-1411	-1654	1	1	1	1
23	4281	99.0%	648	510	508	-1427	-1623	1	1	1	1	4247	645	536	457	-1437	-1609	1	1	1	1	4322	646	525	588	-1387	-1617	1	1	1	1
24	4245	98.2%	650	507	514	-1432	-1628	1	1	1	1	4257	650	535	457	-1450	-1619	1	1	1	1	4355	637	524	576	-1369	-1591	1	1	1	1
25	4273	98.8%	647	510	515	-1414	-1609	1	1	1	1	4264	651	541	450	-1444	-1608	1	1	1	1	4320	645	528	586	-1384	-1610	1	1	1	1

Key to Table 2

V_x	Phase X voltage RMS	$S1_{xO}$	Controller has send signal to operate 800 kVAR/phase stage, phase x
I_x	Phase X current RMS	$S1_{xa}$	Controller received operating ack 800 kVAR/phase stage, phase x
I_{sysX}	Current through actiVAR™, phase X	$S2_{xO}$	Controller has send signal to operate 400 kVAR/phase stage, phase x
P_x	Real load power, phase X	$S2_{xa}$	Controller received operating ack 400 kVAR/phase stage, phase x
Q_x	Reactive load power, phase X	Q_{reqX}	Calculated reactive power to offset load P+Q, phase X

Note: Measurements for each phase are recorded near the time the actiVAR™ valves are fired, and reflect results that are approximately 1/3 cycle apart.

Table 3 – Off Transition *Data Showing actiVAR™ Performance* as Motor Comes Up to Full Speed

Cycle count	Va	Pua	Ia	Isysa	Pa	Qa	QreqA	S1ao	S1aa	S2ao	S2aa	Vb	Ib	Isysb	Pb	Qb	QreqB	S1bo	S1ba	S2bo	S2ba	Vc	Ic	Isysc	Pc	Qc	QreqC	S1co	S1ca	S2co	S2ca
93	4547	105.2%	500	541	453	-1003	-1062	1	1	1	1	4524	498	573	427	-1010	-1057	1	1	1	1	4589	493	560	513	-954	-1040	1	1	1	1
94	4543	105.1%	491	541	452	-978	-1035	1	1	1	1	4529	488	577	428	-982	-1028	1	1	1	1	4598	482	562	522	-920	-1008	1	1	1	1
95	4610	106.6%	479	546	460	-938	-998	1	1	1	1	4553	476	581	426	-946	-990	1	1	1	1	4608	469	566	517	-881	-966	0	1	1	1
96	4621	106.9%	461	546	447	-897	-950	0	0	1	1	4548	452	573	451	-875	-930	0	1	1	1	4536	421	420	506	-770	-849	0	0	1	1
97	4483	103.7%	416	411	449	-802	-855	0	0	1	1	4384	410	392	428	-812	-855	0	0	1	1	4381	404	358	509	-761	-840	0	0	1	1
98	4370	101.1%	397	347	452	-787	-840	0	0	1	1	4352	395	371	431	-795	-839	0	0	1	1	4397	387	362	502	-727	-802	0	0	1	1
99	4408	101.9%	376	350	437	-738	-783	0	0	1	1	4379	371	372	410	-737	-770	0	0	1	1	4456	360	364	466	-667	-725	0	0	1	1
100	4437	102.6%	350	353	409	-678	-710	0	0	1	1	4443	346	378	383	-676	-696	0	0	1	1	4473	333	370	434	-608	-651	0	0	1	1
101	4472	103.4%	320	355	375	-610	-625	0	0	1	1	4477	313	379	348	-606	-609	0	0	1	1	4555	299	373	383	-543	-562	1	0	0	1
102	4500	104.1%	284	354	322	-540	-531	1	1	0	0	4490	275	376	327	-514	-508	1	0	0	1	4415	248	237	347	-432	-433	1	1	0	0
103	4354	100.7%	232	229	297	-433	-412	1	1	0	0	4371	225	199	279	-433	-403	1	1	0	0	4362	215	175	302	-389	-370	1	1	0	0
104	4309	99.7%	203	171	256	-391	-351	1	1	0	0	4354	199	185	237	-392	-344	1	1	0	0	4365	190	179	257	-353	-314	1	1	0	0
105	4369	101.0%	178	174	212	-348	-287	1	1	0	0	4396	172	185	187	-347	-275	1	1	0	0	4416	163	180	201	-312	-246	1	1	0	0
106	4376	101.2%	153	173	162	-308	-224	1	1	0	0	4422	150	187	148	-307	-217	1	1	0	0	4440	142	181	163	-277	-194	1	1	0	0
107	4416	102.1%	135	175	131	-276	-178	1	1	0	0	4456	132	187	115	-274	-169	1	1	0	0	4479	124	181	129	-248	-149	0	1	0	0
108	4445	102.8%	115	173	98	-240	-127	0	0	0	0	4440	109	173	101	-222	-110	0	1	0	0	4391	88	49	110	-165	-58	0	0	0	0
109	4289	99.2%	86	64	101	-169	-58	0	0	0	0	4263	85	19	99	-171	-59	0	0	0	0	4238	84	1	112	-161	-55	0	0	0	0
110	4207	97.3%	82	1	102	-166	-55	0	0	0	0	4236	82	1	100	-166	-54	0	0	0	0	4245	81	0	115	-153	-48	0	0	0	0
111	4196	97.0%	81	0	108	-158	-50	0	0	0	0	4230	80	1	111	-155	-48	0	0	0	0	4245	81	0	125	-145	-43	0	0	0	0
112	4194	97.0%	82	1	122	-153	-50	0	0	0	0	4251	83	1	123	-152	-50	0	0	0	0	4239	82	2	140	-135	-40	0	0	0	0

actiVAR™ Valve Technology

The actiVAR™ valves (schematically shown in Figure 5) are single-phase solid state switches that operate the actiVAR™ stages once per cycle without any mechanical operating limits, current, or voltage transients. The valves consist of series and parallel combination of thyristors and diodes to obtain the required current and voltage ratings of the equipment. The valves also contain voltage dividers for voltage sensing of line and load-side terminal voltages. Thyristor firing boards that gate the thyristors and communicate with the actiVAR™ controller. Over-temperature sensors for thermal overload protection, and RC Snubbers and sharing resistors for transient over-voltage and over-current protection of the thyristors and diodes.

The valves have separate transient and steady-state current ratings. Motor start applications use the transient rating of the valve (which is 2 to 3 times the continuous rating of the valve) as application time is typically on the order of seconds to a minute.

Using a system design with more than one stage provides multiple levels (“steps”) of var compensation, with all levels being available for insertion each cycle. This is illustrated in Table 1 below.

Closing Observations

In observing performance during the motor start, the actiVAR™ controller and switches are clearly fast enough to meet both customer and utility expectations. However, experienced engineering design considering the number of stages and stage size is critical. Clear communications and responsibilities between vendor, consultant (or customer engineer) and end-customer is a critical component of a functional, reliable, economical and successful installation.

The actiVAR™ has characteristics that provide unique advantages in specific types of installations. In this application the system provided voltage support for starting 3 large motors. Nothing special was required, other than careful consideration of where to place the load CT.

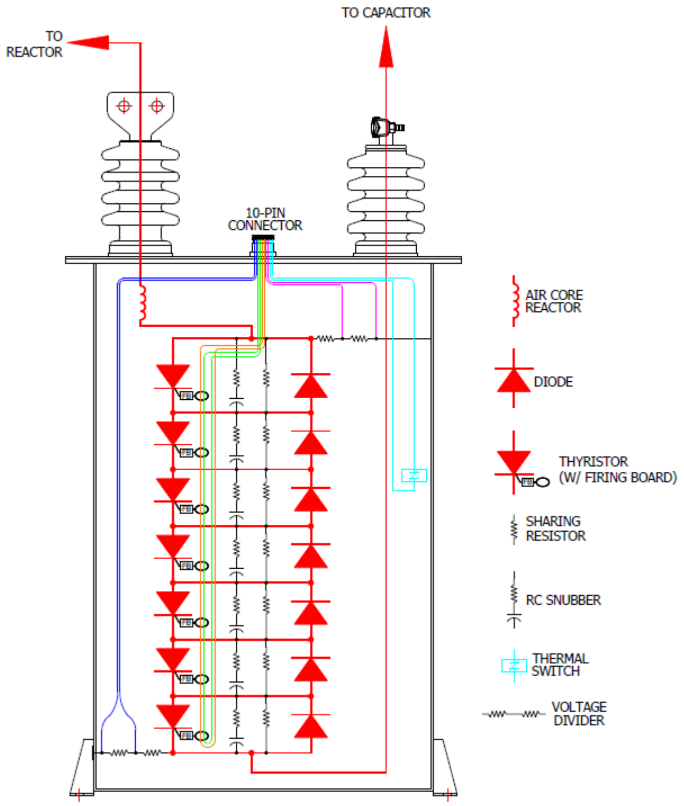

Figure 5 - *Schematic Diagram of actiVAR™ Valve (Thyristor Valve or "Static Switch"). T-Star Engineering and Technical Services supplies NEPSI with the actiVAR™ Valve and Controls.*

Because the controls operate continuously on load P and Q, it is easy to extend operations beyond motor starts to applications where motors rapidly change power draw in response to mechanical demand. Examples include mining (with draglines, hoists, continuous miners, ball mills, cone crushers), recycling (auto shredders), primary metals (hot and cold mills). Step size becomes more critical in these applications as increasing operating frequency results in tighter voltage levels.

NEPSI uses thyristor valves and controllers manufactured by T-Star Engineering. T-Star has designed, built, installed, and maintained over 100 actiVAR™ and thyristor controlled capacitor banks for motor staring and dynamic load applications.