Effect of High Speed Reclosing on Fault Induced Delayed Voltage Recovery

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***Abstract* — This paper presents the effect on fault induced delayed voltage recovery (FIDVR) of high speed reclosing onto a fault. As most of the faults on the system are temporary or transient faults, auto-reclosing is widely used across the industry to reduce the outage time. However, if the voltage recovery following clearing of a fault is slow and if the fault is permanent in nature, auto-reclosing on to a fault could increase voltage recovery time significantly. This is especially true for the case where the fault cannot be cleared instantaneously. This is may be because the line does not have a pilot protection scheme or the pilot is out of service and the fault is located outside the zone 1 reach of the reclosing end breaker. This paper presents the simulation of this scenario on some of the 230kV lines around the metro Atlanta area. Finally, this paper also discusses a few solution options, if auto-reclosing onto a fault poses a threat of a FIDVR event.**

***Index Terms* — High Speed Reclosing, Auto-Reclosing, FIDVR, Voltage Recovery, Voltage Stability**

I. INTRODUCTION

Fault induced delayed voltage recovery is a phenomena where the system voltage remains at significantly reduced levels for several seconds after a transmission, sub-transmission or distribution fault has been cleared [1]. This could result in the loss of load and generation or fast voltage collapse. Generally, heavily loaded induction motors tend to slow down and consume more reactive power during a period of low voltage created by a fault on the system resulting in further depression of transmission voltage. Major factors in slow voltage recovery following a fault include duration and type of fault, fault location and lack of dynamic MVAR support on the system as well as high penetration of induction motor load.

On July 30th, 1999, the Southern Control Area experienced a multi-fault event during which the transmission system experienced delayed voltage recovery which lasted as long as 15 seconds [2]. As a result, 1900MW of load was lost. In addition to the load loss, seven generating units tripped with a total output of 1065MW, during or minutes after the event. It is important to mention that only 100MW of load was tripped due to utility breaker operation. So the majority of load lost was due to induction motor protection. Figure 1 shows the voltage measured at a generating plant approximately 50 miles away from the fault location for this event. Also, during this event, automatic reclosing was utilized in an effort to minimize the duration of resulting outages.

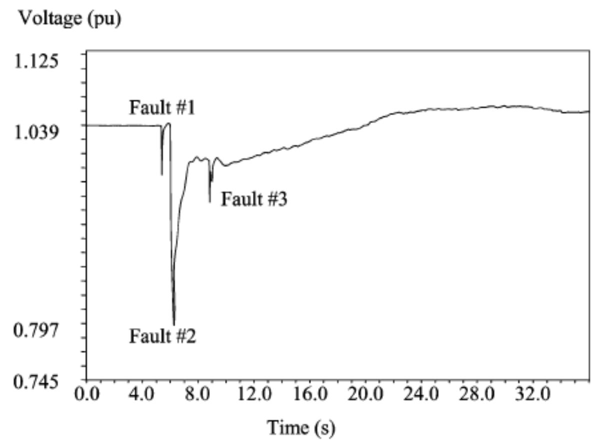

Fig. 1. Voltage plot showing delayed voltage recovery of 1999 event

As previously mentioned, fault duration is one of the major factors affecting slow voltage recovery following a fault. High speed automatic reclosing is another factor which can directly affect fault duration during an event, if the fault is permanent in nature. Many studies have shown that anywhere from 70% to as high as 90% of faults on overhead transmission lines are temporary or transient faults, such as lightening, swinging conductors, temporary contact with trees etc. Usually transient faults disappear after a short dead time and hence can be cleared by momentarily de-energizing the line. The line can then be re-energized by auto-reclosing from one end first, which is usually a strong source. The remaining 10-30% of faults are semi-permanent or permanent in nature. A small branch falling onto the line can cause semi-permanent fault. Such faults usually requires more than one de-energized interval before it disappears. Permanent faults such as broken conductor or pole, tree leaning on the line etc. will not clear upon tripping and reclosing. They must be traced and removed to restore service. Because most of the faults on the system are temporary faults, auto-reclosing can significantly reduce the outage time and provide higher level of service continuity to the customer. This is especially true for lines with tapped load. In addition to the previously mentioned benefits, successful high speed reclosing on transmission lines can be a major factor when attempting to maintain system stability.

Auto-reclosing is widely used in one form or another across the industry [3]. While the impact of high speed reclosing on the angular stability of machines connected to the system has been widely discussed [4-5], this paper specifically presents the impact of high speed reclosing on fault induced delayed

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voltage recovery. If the voltage recovery of the system after clearing of a fault is slow then it is possible that high speed reclosing onto fault could hurt the system further in terms of voltage recovery. This is especially true for the case where the fault cannot be cleared instantaneously. This is may be because the line does not have a pilot protection scheme or the pilot is out of service and the fault is located outside the zone 1 reach of the reclosing end breaker. This study simulates faults on 230kV lines around the metro Atlanta area in the North Georgia portion of the Southern Company system.

II. Reclosing Practice

This section summarizes the reclosing practice used on 115kV and 230kV transmission line breakers at Southern Company [6]. While 115kV and 230kV networks are comprised of ring, breaker-and-a-half and straight bus configurations, the straight bus configuration is the predominant configuration in Georgia. For breaker-and-a-half and ring bus configurations, two breakers share a particular line and one of these breakers is designated as the test breaker.

For most 115kV and 230kV lines, the reclose sequence is specified as two reclose shots, at 0 and 15 seconds. Almost all 115kV and 230kV breakers have reclosing in service at all times. Usually the breaker at which the Dead Line (DL) switch is closed or enabled is used to test the line after successful clearing of a fault on the line. A Closed or Enabled DL switch means that the breaker is allowed to close if the line is de-energized and the bus is hot. Therefore, the position of DL switch designates whether the breaker is the test breaker for line faults or not. After the successful clearing of a fault on the line from both ends, a test breaker will reclose to test the line. If the reclose attempt is successful, the remote breaker with the DL switch open will reclose automatically after the line has been re-energized for 2 seconds. For ring and breaker-and-a-half bus configurations, only one of the breakers is the test breaker. In these configurations the other non test breaker will reclose automatically after a 2 second time delay.

For the line shown in figure 2, breaker 001 at station 'A' is the test breaker as the DL switch is closed. DL switch for breaker 002 and station 'B' is open. After the successful clearing of a fault on the line, breaker 001 recloses to test the line. If the fault has disappeared, breaker 002 will reclose after 2 second time delay. If the first reclose shot is unsuccessful, i.e. the fault still exists on the line; breaker 001 will test the line one more time after 15 second time delay. Breaker 002 will follow if second reclose attempt is successful after 2 second time delay.

III. Study Assumptions

The reclosing duty cycle of most breakers used is O + 0.3S + CO + 15S + CO where 'C' is for Close and 'O' is for Open. This means that the breaker has 0.3 seconds or 18 cycles, of dead time before the first reclose shot so that it can withstand reclosing onto a permanent fault without deteriorating its fault interruption capacity. The dead time for a second reclose shot is 15 seconds. The dead time is usually followed by the time it takes for the breaker to mechanically close the contacts, which is usually in order of 7-10 cycles. So even though the reclosing relay does not have any intentional time delay, it may take as long as 25-28 cycles for the breaker to close following successful clearing of the initial line fault. For this study, the dead time before the first reclose shot is assumed to be 25 cycles, which represents the most conservative scenario.

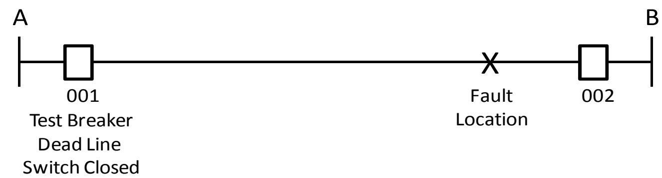

Fig. 2. Transmission Line

This study assumes a scenario in which pilot protection scheme is out of service or line doesn't have pilot protection and the Zone 1 relay reach on each line is assumed to be 85% of the line impedance. A three phase fault was placed at the end of zone 1 reach from the end at which the Dead Line switch is closed or enabled. For the line shown in figure 1, the fault is placed at 85% of the line impedance from station 'A'. It is assumed that breaker 002 at station 'B' clears the fault in 1 cycle relay pickup time + breaker 002 clearing time. Breaker 001 at station 'A' clears the fault in 1 cycle relay pickup time + zone 2 time delay + breaker 001 clearing time. The dead line switch is closed at station 'A' to allow breaker 001 to reclose to test the line. If the fault still remains on the line, breaker 001 at station 'A' clears it again in relay pickup time + zone 2 time delay + breaker 001 clearing time. If the fault has cleared, breaker 002 at station 'B' will reclose after an additional 2 second time delay.

It is important to note that, usually switch-on-to-fault protection is used or applied to trip the breaker instantaneously if it recloses on to a fault, usually for fault at any location on the line. However, this type of protection scheme is only implemented on ring bus breakers on the Southern Company system. Straight bus breakers do not have switch-on-to-Fault protection enabled. This will result in delayed clearing of zone 2 faults on lines connected to straight bus breakers.

Table I shows a sample sequence of event assuming a 1 cycle relay pickup time, 25 cycle zone 2 time delay and 3 cycle breaker clearing time. Because the second reclose shot is delayed by 15 seconds, it is not a concern for this study.

The dynamic load model structure and parameters used for this study were developed to duplicate the 1999 event discussed in [7] when approximately 1900MW of load was lost and delayed voltage recovery was recorded. Figure 3 shows the load model structure used in this study.

TABLE I
SEQUENCE OF EVENT

Time (cycles)	Event
0	Inception of fault at 85% of line impedance from station 'A'
4	Breaker 002 clears the fault as the fault is in zone 1 reach
29	Breaker 001 clears the fault since the fault is outside zone 1 reach
54	Breaker 001 recloses to test the line after a 25 cycle open interval
83	Breaker 001 clears the fault again

Based on the analyses of 1999 event, 50% of total real power load is assumed to be induction motor load and the remaining is modeled as constant current load. The remaining reactive load is modeled as constant impedance load. Because the actual load is connected to the distribution feeders, which are not modeled in power flow cases (loads in power flow cases are presented at transmission buses), a distribution system impedance of 0.01 + j 0.10 PU is selected to better approximate the average voltage actually seen by the motor terminals.

IV. Simulation Results

The study was performed on a 2011 summer peak case. Table II shows the voltage recovery time in seconds for faults on various 230kV transmission lines around metro Atlanta area. The faults are placed at the end of Zone 1 reach from the reclosing end of the line.

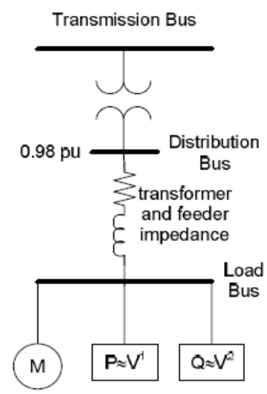

Fig. 3. Load Model Structure

The recovery times are noted for the last bus to recover to 0.8PU voltage after the fault is cleared. It is expected that once the voltage recovers to 0.8PU, it will continue to recover to normal operating voltage within a reasonable time.

With expected generation dispatch, the voltage recovers fairly quickly after the fault is cleared first time and before the breaker recloses onto the fault. Hence, when the breaker recloses onto the fault it is considered an independent event and not the continuation of the first event. In such cases, even though the breaker recloses onto a fault, it does not pose the threat of a FIDVR event. After the second time the breaker clears the fault, voltage recovers almost instantly. Figure 4 shows the voltage recovery plot of the last bus to recover to 80% voltage for a three phase fault located on the Cecil – South Gillian 230kV line at the end of zone 1 reach from South Gillian.

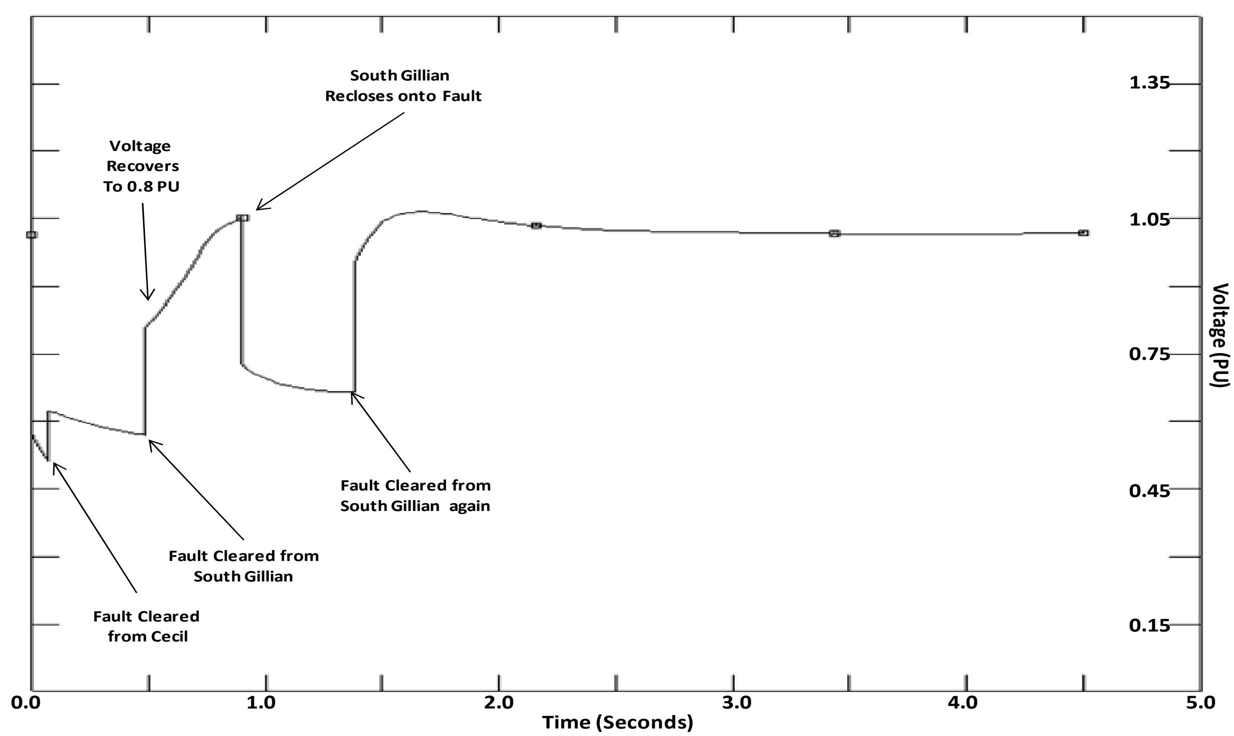

Fig. 4. Voltage Recovery Plot for fault on Cecil - South Gillian 230kV line at the end of zone 1 reach from South Gillian

TABLE II
SIMULATION RESULTS FOR 2011 PEAK CASE

		Voltage Recovery Time in Seconds			
		Expected Dispatch		Just FIDVR Secure Case	
230kV Line (From - To)	Reclosing End	without Reclose	with Reclose	without Reclose	with Reclose
Cecil - S. Gillian	S. Gillian	0.5416	1.3833	1.6999	DNR*
Jade - DenaCircle	Jade	0.3583	1.0333	0.7499	1.1416
Taylor - West Henrietta	Taylor	0.2916	0.9166	0.5999	1.0249
Taylor - Woodbridge	Taylor	0.4083	0.9999	0.9833	3.9333
Madyson - Alexander	Madyson	0.4916	1.0666	1.2916	DNR*
DenaCircle - Alexander	DenaCircle	0.4999	1.0666	1.3916	DNR*
Adamson - Reed	Reed	0.3749	1.1499	0.6666	1.1499
Reed - Cameron	Reed	0.2749	0.9666	0.3749	0.9666
Dennis - Aden	Dennis	0.4583	1.1666	0.8999	1.3666
Lea - Kedrick	Kedrick	0.4666	1.0166	1.1749	DNR*
Piper - Lucas	Piper	0.4083	1.0499	0.7166	1.2416
Frederickson - Marion	Marion	0.5499	1.2666	1.3083	5.4166
Marion - Audrel	Marion	0.6333	1.2833	1.8749	DNR*
Marion - Mack	Marion	0.4833	1.1833	1.0166	2.1166
Marion - Sheldon	Sheldon	0.3333	1.0499	0.5749	1.0499
Kedrick - Colton	Colton	0.4916	1.3833	0.9833	1.3999
Aden - Bradley	Bradley	0.6083	1.3833	4.1582	DNR*
Reed - Bradley	Bradley	0.5916	1.3833	6.8915	DNR*
Marion - Carmen	Marion	0.4833	1.3833	0.6833	1.3833
Alfred Drive - Kedrick	Kedrick	0.5166	1.3833	1.0583	1.7916
Grady - Kedrick	Kedrick	0.5583	1.3833	1.4916	DNR*

*DNR: Voltage did not recover within 8 seconds. Simulation was stopped at 8 seconds.

As shown in figure 4, the fault is cleared from Cecil and South Gillian in 0.0667 seconds (4 cycles) and 0.4833 seconds (29 cycles) respectively. In this case, the last bus on the system recovers to 80% voltage in 0.5416 seconds (32.5 cycles), which is prior to the time at which the breaker at South Gillian will reclose onto the fault. The South Gillian breaker recloses onto the fault at 0.90 seconds (54 cycles) and clears the fault for the second time at 1.3833 seconds (83 cycles). Voltage then recovers nearly instantly. This nearly instant voltage recovery following the second clearing of the line fault is observed for every other line for which the simulation was performed.

Table II also shows the simulation results for a just FIDVR secure case. A just FIDVR secure case presents a more conservative generation pattern which is different from an expected dispatch, such that the longest voltage recovery time to 80% voltage is approximately 2.0 seconds for a worst normally cleared fault on the system with one cycle fault clearing margin. Mainly, some generation is moved away from metro Atlanta area in this case. Under this conservative generation assumption, the voltage recovery for faults on lines mentioned in Table II, takes quite a bit longer, and in some cases does not recover at all. This is due to the fact that the reclosing end of the line closes onto a fault to test the line before voltage has fully recovered following clearing of a fault the first time.

Figure 5 shows the voltage recovery plot for the last bus to recover to 80% voltage for a three phase fault located on the Taylor - Woodbridge 230kV line at the end of zone 1 reach from Taylor. As shown in figure 5, without considering auto-reclosing, the last bus recovers to 80% voltage in 0.9833 seconds (59 cycles). Given that the line has auto-reclosing scheme enabled, the Taylor end of the line recloses onto the fault at 0.7083 seconds (42.5 cycles), which is prior to the time at which the last bus of system has recovered to 80% voltage. This causes the voltage to stay depressed for 3.9333 seconds from the inception of the fault.

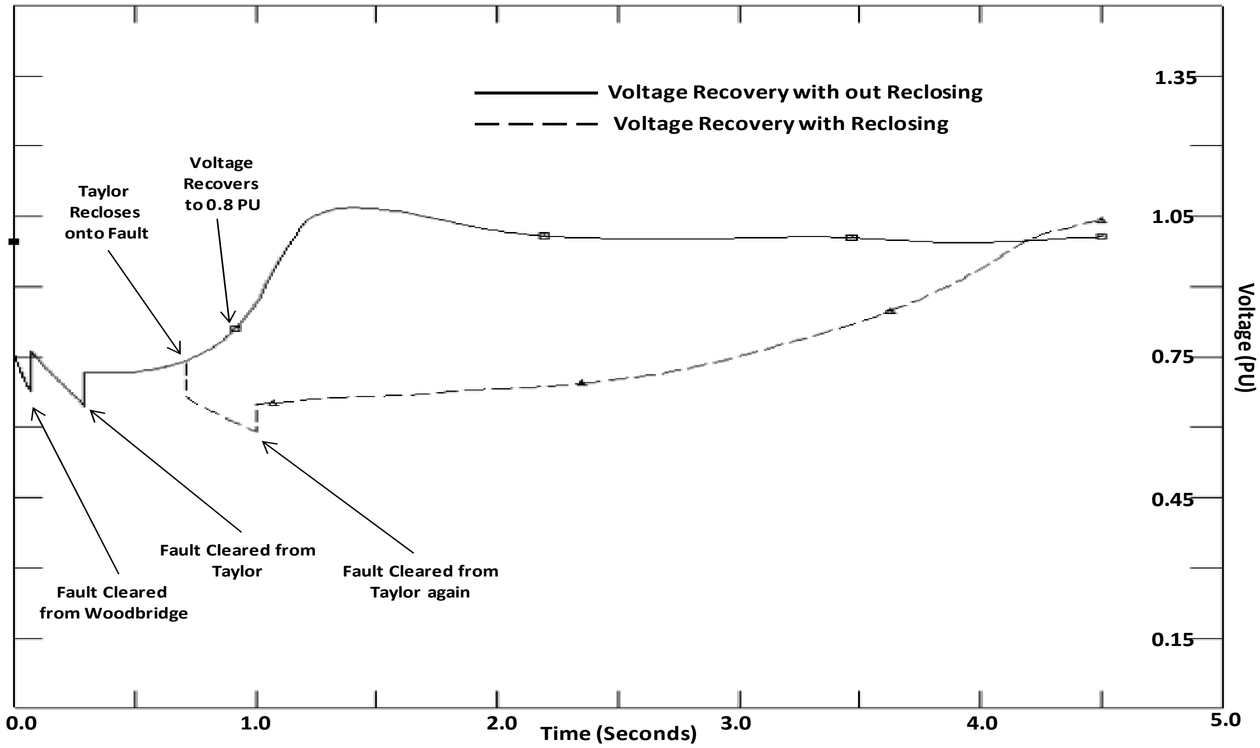

Fig. 5. Voltage Recovery Plot for fault on Taylor – Woodbridge 230kV line at the end of zone 1 reach from Taylor

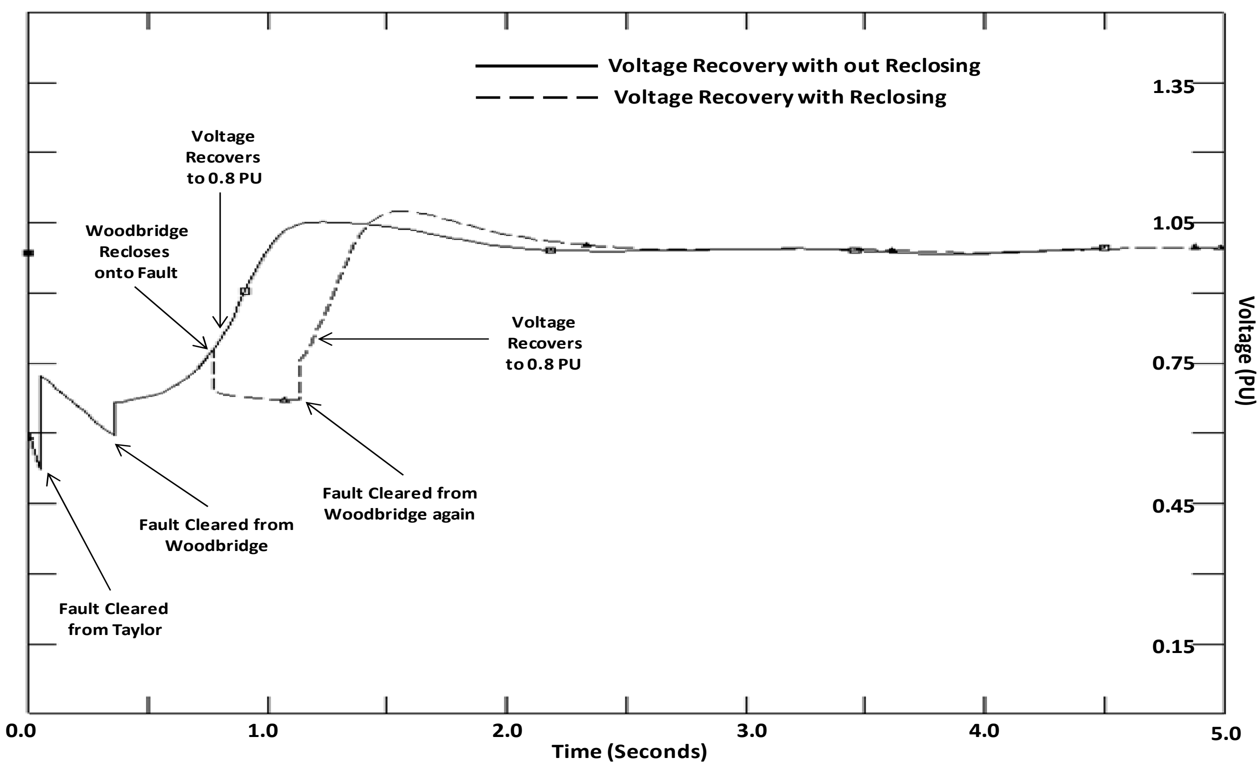

Fig. 6. Voltage Recovery Plot for fault on Taylor – Woodbridge 230kV line at the end of zone 1 reach from Woodbridge

Due to auto-reclosing onto a fault, voltage recovery for the last bus on the system to 80% voltage takes 3.9333 seconds compared to 0.9833 seconds without reclosing. Similar observation can be made for several other lines as shown in Table II. This is not a great concern because the amount of generation that has been turned off in metro Atlanta area and moved away to simulate a just FIDVR secure case is greater than normal. In future years, if the differences between the generation pattern available through expected dispatch and the generation to stay FIDVR secure become fewer, reclosing onto faults could become a concern. In such situations, the obvious solution is to increase the reclosing time interval. This delay provides more time for the system voltage to recover to the pre-fault level before reclosing on to a fault. Another approach to this issue is to reduce the zone 2 timer settings taking care to ensure it co-ordinates with remote breaker failure clearing times. This reduces the time that a zone 2 fault stays on the system and allows the system voltage to recover more quickly before reclosing on to a fault. One final approach is to use the breaker with a weaker source behind it as a test breaker for line faults, if appropriate. Usually, the breaker with a strong system source behind it is used as the test breaker for line faults. From a FIDVR perspective, a fault fed from a strong source is much worse when compared to feeding it from a weak source for the same time duration. This outcome is demonstrated in figure 6. It shows the voltage recovery plot of the last bus to recover to 80% voltage if the breaker at Woodbridge is chosen as a test breaker instead of the breaker at Taylor for faults on the Taylor – Woodbridge 230kV line. Note that with auto-reclosing, the voltage recovers in 1.1833 seconds with the Woodbridge breaker as a test breaker compared to 3.9333 seconds with the Taylor breaker as a test breaker. Based on fault MVA values, the system behind the Taylor bus is a much stronger source than the system behind the Woodbridge bus. In this example, choosing the Woodbridge breaker as a test breaker results in faster voltage recovery.

V. Conclusion

This paper presents the effect of high speed reclosing onto a fault on FIDVR. The intent of this study was to identify if auto-reclosing of transmission line breakers after clearing of a fault is going to delay voltage recovery of the system. As a result, it is identified that this is not a problem with today's generation pattern and given load level. It is also identified that if the generation pattern changes in future, such that, more power is imported into the metro Atlanta area from remote locations, automatic reclosing on transmission lines could become a concern. This paper presents three possible mitigation options to this problem.

VII. References

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VIII. Biographies

Jonathan Glidewell (M'2001) received his B.S. in Electrical & Computer Engineering from the University of Alabama at Birmingham in 2001. He began working in Transmission Planning Department at Southern Company Services in 2001. He has worked in Transmission Planning since then except for one year during 2008-2009 when he worked in Operations Planning. He is currently a Project Manager in Transmission Planning and a registered Professional Engineer in the state of Alabama.

Manish Patel (S'2004-M'2007) received his B.E. from B. V. M. Engineering College, V. V. Nagar, India in 2000 and Ph.D. from Clemson University, Clemson, SC in 2009, both in Electrical Engineering. He joined Georgia Power Company in 2006 as a Protection & Control Engineer. In 2010, he joined Transmission Planning Department of Southern Company Services. He is currently involved in stability studies of Southern Company Grid.