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A Historic Perspective of Power System Disturbances in the Southern African Power Pool (SAPP)

S.K. ZIMBA[1], A.M. CHIKOVA

Southern African Power Pool (SAPP)

Zimbabwe

[1]Corresponding author: sydneykadikulazimba@yahoo.com

Abstract— In the southern African region, electric power systems of nine countries are interconnected. Advantages of an interconnection include reduction of overall cost for supplying power, enhancing power system reliability, promoting environmental sustainability, and fostering regional integration. However, interconnections make the power system big and complex. This brings about operational challenges. One of the main operational challenges is the occurrence of power system disturbances emanating from within or across borders. The power system in the southern African region has undergone a lot of developments since the formation of the Southern African Power Pool (SAPP) in 1995. New interconnectors have been commissioned at different stages. SAPP has also seen new developments in the physical configuration of the existing power system for operations. Occurrence of power system disturbances in SAPP was investigated in relation to the above mentioned developments. This paper presents the historical development of the SAPP power system. Then it highlights power system disturbances that occurred in SAPP from 2003 to 2016. The paper also discusses efforts that have been made to mitigate the disturbances. It is observed that the nature of most system disturbances is influenced by new developments in the power system. Penetration of renewable energy sources, increased distributed generation, and interconnection between SAPP and East Africa Power Pool (EAPP) are some of the eminent new developments in SAPP in the short to medium term. As the interconnected power system grows, there is need to learn from historic trends of system disturbances. This may facilitate development of a resilient power system.

Keywords— *electric power systems; interconnection; disturbance; blackout; power pool; Southern Africa; SAPP*

I. INTRODUCTION

Most technologies for producing electric power exploit natural resources including fossil fuel, hydro-power, natural gas, and minerals like uranium. Countries have varying quantities of natural resources for producing electric power. Some countries produce sufficient electric power to meet and even exceed their national demands. However, other countries, due to various constraints, do not meet their national demands. The cost of producing, transporting and distributing power varies from country to country. Therefore, national power utilities interconnect their transmission systems to trade electricity. This reduces the total cost of power supply, enhances power system reliability, reduces the overall impact on the environment, and fosters regional integration [1],[2],[3],[4].

Fig. 1 below shows the geographic map of the southern African region, highlighting major routes of power lines. Power systems of nine countries (Botswana, Democratic Republic of Congo, Lesotho, Mozambique, Namibia, Republic of South Africa, Swaziland, Zambia, and Zimbabwe) are interconnected[1]. In 2016, the installed generation capacity and the energy consumption within SAPP were 57 917 MW and 360 471 GWh, respectively [1]. Power utilities in every continent have realized a number of technical advantages from interconnections, including: voltage support, sharing reserves, and energy assistance during power supply emergencies [5],[6].

1 Interconnected SAPP power utilities are: BPC: Botswana Power Corporation; CEC: Copperbelt Energy Corporation (of Zambia); EDM: Electricidade de Mozambique (North and South); Eskom: Eskom Holdings (of RSA); HCB: Hidroeléctrica de Cahora Bassa (of Mozambique); LEC: Lesotho Electricity Company; LHPC: Lunsemfwa Hydro Power Company; SEC: Swaziland Electricity Company; SNEL: Société Nationale d'Electricité (of DRC); ZESA: ZESA Holdings (of Zimbabwe); and, ZESCO: ZESCO Limited (of Zambia)

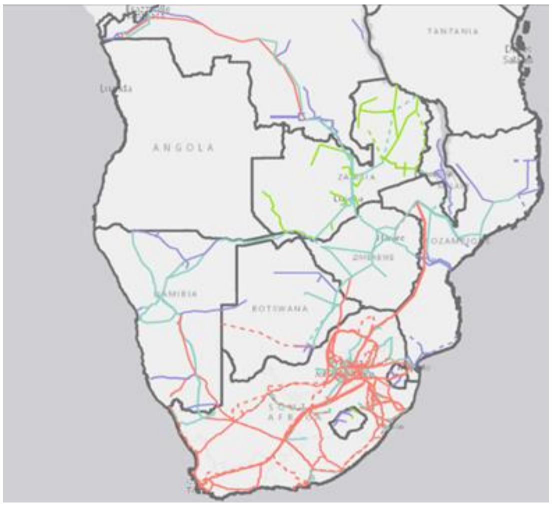

Fig. 1: Map of southern Africa, showing routes of main transmission lines including cross-border interconnectors.
Source: IRENA: 2015

Generally, in the southern African region, most power systems were designed for isolated operation, supplying national loads. Apart from few historical cross-border lines, most interconnectors were commissioned after 1995 when the Southern African Power Pool (SAPP) was formed [1]. With each new interconnector and new generation and transmission equipment, the SAPP interconnected power system has grown. Large power systems are complex. Oftentimes, complexity brings operational challenges that threaten power system reliability [6].

One of the major challenges of interconnection is occurrence of power system disturbances, emanating from within or across the borders. According to the SAPP Operating Guidelines, a system disturbance is defined as an event that results in abnormal power system conditions [7]. These abnormal conditions may damage equipment or may interrupt power supply contracts [7]. System disturbances are very costly, as seen in the Croatia case in reference [8].

Since the formation of SAPP in 1995, the interconnected power system has experienced numerous disturbances. Power utilities in SAPP have made various efforts to minimize the number and impact of these disturbances.

The objective of this paper is to present major developments in the SAPP interconnected power system and to discuss system disturbances that have occurred in SAPP over the years, including efforts made to mitigate them. The main data of this investigation were obtained from official SAPP annual reports.

The remainder of this paper is divided into five sections. Sections II and III present major developments in the SAPP interconnected power system. Section IV presents typical system disturbances that occurred in SAPP. Mitigation measures plus lessons learnt are discussed in Section V. Lastly, conclusions and recommendations are made in Section VI and Section VII, respectively.

II. NEW INTERCONNECTOR DEVELOPMENT

Owing to historic bilateral agreements, some SADC countries were already interconnected prior to the formation of the SAPP. Early interconnections were between DR Congo and Zambia, between Zambia and Zimbabwe, and between South Africa and its neighbouring countries. However, these interconnections were weak. Development of new interconnectors to strengthen the interconnected power system happened at different stages. Most interconnectors changed the configuration of the power system and influenced the nature of system disturbances. Refer to Appendix 1 for SAPP interconnectors.

A. Interconnecting Zimbabwe and South Africa: The 400 kV Insukamini (Zimbabwe) – Matimba (South Africa) interconnector was commissioned in 1995. This interconnector was routed through Botswana. Then, in 1998, a T-off substation was commissioned at Phokoje in Botswana to tap from this interconnector. By interconnecting Zimbabwe and South Africa, the following two big masses were connected by a weak link: 1) the predominantly thermal power systems in the south (Botswana, South Africa); and, 2) the predominantly hydro-power systems in the north (Zimbabwe, Zambia, Northern Mozambique, DR Congo). Therefore, the interconnection was susceptible to inter-area power oscillations [9].

B. Interconnecting Zimbabwe and Mozambique North: The Songo (Mozambique) – Bindura (Zimbabwe) interconnector was commissioned in 1997. The line was designed at 400 kV but was energised at 330 kV to economically integrate into the 330 kV national grid backbone in Zimbabwe. This new development provided an alternative source of power injecting into the SAPP central grid from HCB in Mozambique.

C. Commissioning the HVDC Link between Mozambique and South Africa: The 533 kV HVDC link from Songo (Mozambique) to Apollo (South Africa), with a capacity of 1920 MW, was installed prior to 1995. For some time, it was out of service. Then, it was re-commissioned in 1998 [10]. This created a parallel asynchronous path for power flow from northern Mozambique to the southern systems, including Eskom.

D. Interconnecting South Africa and Mozambique via Swaziland: Prior to 1995, South Africa was already connected to southern Mozambique at 275 kV and 110 kV. However, in 2000, the following two major interconnectors, taking different routes, were commissioned: the 400 kV Arnot (South Africa) – Maputo (Mozambique) interconnector; and, the 400kV Camden (South Africa) – Edwaleni (Swaziland) – Maputo (Mozambique) interconnector. These lines were build and operated by the Mozambique Transmission Company (MOTRACO) mainly for the Mozal smelter plant in Mozambique with a peak load of 1000 MW. The second line was deliberately routed through Swaziland to facilitate power interchange with Swaziland.

E. Interconnecting South Africa and Namibia: Prior to 1995, South Africa was already connected to Namibia at 220 kV. In 2000, the 400 kV Aries (South Africa) – Kokerboom (Namibia) interconnector was commissioned.

F. The NamPower Caprivi HVDC Link: Prior to 1995, Zambia was supporting Namibia in the Caprivi Area via a radial 66 kV line, crossing the Zambezi River. This line was later upgraded to 220 kV. However, in 2010 the 350 kV HVDC link from Zambezi Substation near the Zambian border to Gerus in central Namibia was commissioned. Owing to the bidirectional properties of this HVDC link, it rendered another parallel route for both north-south and south-north power flows.

F. Interconnecting Zambia and DR Congo: The old interconnector from Zambia to DR Congo was from Michelo to Karavia via Kasumbalesa. In 2016, the following two more interconnectors were commissioned between Zambia and DR Congo: 220 kV Luano - Karavia and 220 kV Michelo - Karavia. These did not only increase the capacity of the interconnection but also assisted in mitigating low voltages.

III. NEW OPERATING CONFIGURATION AND STATE

New developments in the interconnected power system are not only limited to new generation, transmission and distribution equipment. But, they also include changes in the physical configuration and operating state of the existing interconnected power system, as summarized below.

A. Parallel Operation of HVDC and AC Loads at Songo (Mozambique): Songo is a substation at HCB in Mozambique. The 220 kV main and reserve bus bar system at Songo can be configured to assign generating units to HVDC loads or AC loads. The main and reserve bus bars are linked by the bus coupler circuit breaker. In the years up to 1999, this circuit breaker was operated as a normal open point. However, loads on the AC side grew. One generator was not sufficient for supplying Mozambique north and exporting via Zimbabwe. Therefore, to optimise generation at HCB, the new configuration kept the 220 kV bus coupler circuit breaker in closed position [10]. See Fig. 2 below. This circuit breaker is very important as it links loads on the HVDC and AC circuits. When it trips, it brings its own challenges in the interconnection.

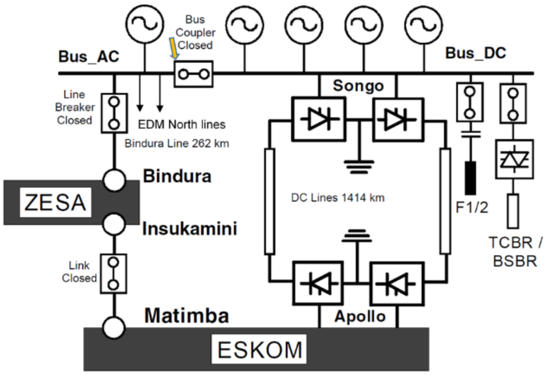

Fig. 2: Simplified diagram of the interconnection between HCB and Eskom. Source: Goosen et. al. (2003) [10]

B. DR Congo Changed from a Net Exporter to a Net Importer: For many years up to around 2006, DR Congo had surplus cost effective hydro-power. The net power flow was from DR Congo to Zambia. In Zambia, the main load centres are in the north of the country, in the Copperbelt province. Yet, the main power stations are in the southern part (Kariba North and Kafue). Therefore, southwards power flows from DR Congo assisted in stabilizing voltages and reducing losses in Zambia. However, due to non-availability of some generating units and due to increase in load in DR Congo, from around 2006 DR Congo started importing power. The general direction of power flow suddenly changed from southwards to northwards. Oftentimes, this resulted in low voltage in the previously mentioned load centres in Zambia.

C. Reduced Maintenance Activities: The great global recession of 2008-2009 [11] affected some SAPP member countries. Scarcity of resources including materials, spares and labour led to reduced maintenance activities on a generally aging generation and transmission asset base. Also, along some transmission lines, vegetation was not being cleared.

D. Power Supply Deficiency: For the year leading up to 2008, the SAPP was in a state of power supply deficiency. This was attributed to delays in implementing generation projects against rising demand. Therefore, most power utilities implemented various load reduction programmes, including loadshedding. Further, most members struggled to keep the required minimum amounts of operating reserves [1].

E. Implementation of Competitive Markets: In SAPP, electricity is traded through bilateral contracts or competitive markets. In 2009 the SAPP Day Ahead Market (DAM) was re-opened. SAPP members utilities were inclined towards optimizing transmission equipment for trading. In some cases, they operated power systems close to stability limits. According to [20], this is common under deregulation and has made power systems more vulnerable to disturbances.

F. Drought in the SAPP Region: In the years leading up to 2016, the SAPP region experienced a drought. The water reservoirs for major hydro-power stations in Zimbabwe (Kariba South), Zambia (Kariba North) and DR Congo (Nseke) reached bare minimum levels. Power generation had to be reduced to prevent depletion of water reservoirs. However, South Africa had surplus generation from new and old thermal power plants. Therefore, big volumes of power could be scheduled from South Africa to Zimbabwe, Zambia and DR Congo.

IV. OCCURRENCE OF SYSTEM DISTURBANCES

Because of weak connections, equipment failure, hidden failures in protection systems, human error and other factors, system disturbances cannot be eliminated in power systems [12],[13]. A SAPP system disturbance is the one which results in interruption of scheduled energy interchange among power utilities or results in excursion of power system frequency outside the 50±0.50 Hz band. Between 2003 and 2016, a total of 393 system disturbances were reported [1]. Refer to Fig. 3 and Fig. 4 below for further details.

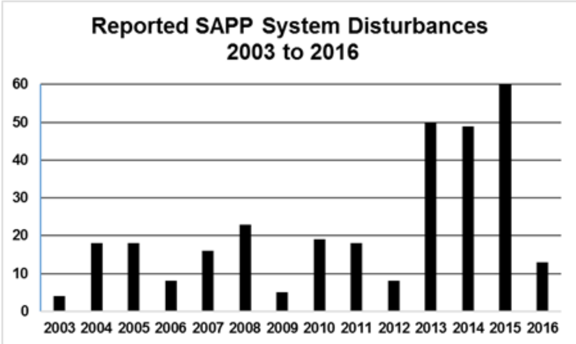

Fig. 3: Disturbances Classified by Year
Source: SAPP [1]

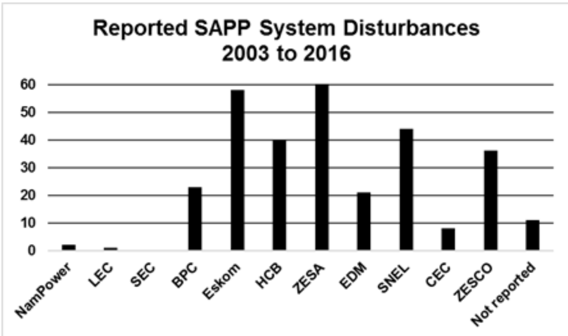

Fig. 4: Disturbances Classified by Utility
Source: SAPP [1]

These disturbances were studied. Their causes were summarised below. Most of these disturbances were characterised by un-damped power oscillations and cascaded equipment failure.

A. Causes of Reported SAPP System Disturbances

1) Faulty Auxiliary Systems: The greatest number of system disturbances was caused by faulty auxiliary systems at power plants. When such essential systems as cooling systems, lubricating systems, measurement systems were disturbed, generators tripped. Oftentimes, this resulted in power system frequency excursions, especially in the state of deficient operating reserves. In isolated cases, frequency excursions were caused by loss of large customer loads or sudden increase of load prior to dispatching generation.

2) Faulty Equipment: The second greatest number of system disturbances was caused by faulty line equipment. These faults included broken conductors, collapsed towers, and broken insulators. Also, failure of line terminal equipment, transformer components, and HVDC converter bridges, mainly due to old age, were common causes of disturbances.

3) Adverse Weather Conditions: Heavy rains and thunderstorms broke down insulation. Lightning caused transient faults on power lines. In few disturbances, landslides and floods washed away transmission towers.

4) Vandalism: Some disturbances were caused by vandalism of transmission equipment by people, mainly for perceived economic gains.

5) Human Error: Disturbances caused by human errors during switching were few. But they caused major adverse impact, including shutting down of large power stations and partial blackouts.

6) Bush Fire: Bush fire along the line routes led to breakdown of insulation. In some cases, the fire was set by farmers as part of agricultural activities.

7) Protection Mal-operation: In some disturbances, protection relays sent spurious commands to trip circuit breakers. In other disturbances, protection systems over-reached. In mitigation, maintenance and coordination of protection systems was enhanced.

8) Birds and Animals: Birds nesting on towers and monkeys playing in live high voltage substations caused disturbances. In one disturbance, a cat caused a short circuit on a transformer bushing in an in-door substation at a major power station.

9) Equipment Tests: One disturbance was attributed to scheduled load rejection tests at a new power station.

10) Induced from Distribution: Some through-faults from distribution systems affected the transmission system. The faults were common at a 330/220/33 kV interconnection transformer in Mozambique. At one time, a distribution load had been temporarily connected to the tertiary winding of this transformer. The transformer used to trip because of faults emanating from the 33 kV distribution line. Subsequently, the distribution line was disconnected from the tertiary winding and the load was supplied from a new proper substation.

11) Overload and Under-voltage: Power systems in the north drew more power than scheduled. Because of this, a line in central corridor tripped on overload. This led to cascading tripping of other equipment. In other disturbances, increased power transfers led to under-voltage. Some loads tripped on under-voltage.

B. Examples of Major System Disturbances

This section gives a summary of three typical disturbances that occurred.

1) Tripping of Converter Bridge at HCB Songo Converter Station in Mozambique: On 12 January 2010 at 17h33:17:005 the Converter Bridge no. 3 tripped at Songo due to a converter valve pulse amplifier differential protection (commutation failure). At Apollo in Eskom, Converter Bridge no. 7 inter-tripped, interrupting 290 MW of Eskom's imports. At 17h33:17:680 the Songo 220 kV bus coupler circuit breaker tripped due to excess-energy protection. The HCB – ZESA interconnector remained in service but with un-damped power oscillations. Refer to Fig. 5 and Fig. 6 for plots of power system elements. Subsequently, in ZESA, a number of transmission lines tripped because of the oscillations, splitting the interconnected system in the process. Three generators tripped at Hwange and one at Kariba South, losing about 480 MW of generation. The ZESCO and Eskom systems quickly stabilised. The interconnected system was then re-synchronised at 18h29.

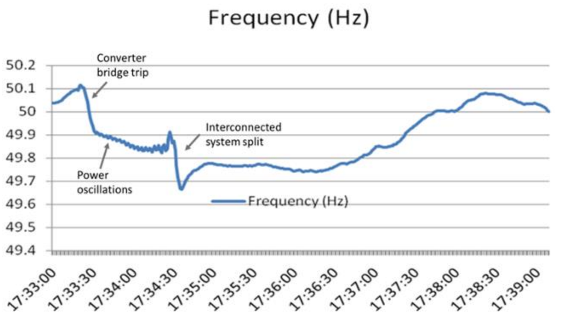

Fig. 5: Frequency plot _ 12 January 2010

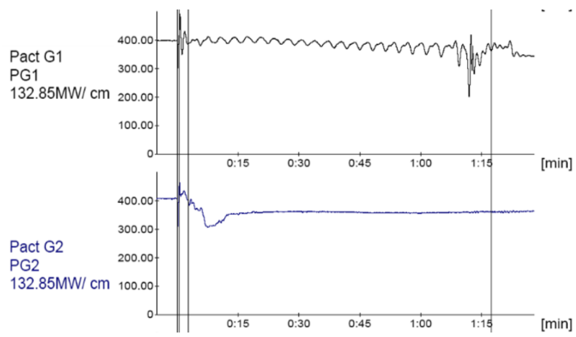

Fig. 6: HCB G1 and G2 Electrical Power Plots _12 January 2010

2) Tripping of Transformers at Kitwe in Zambia: On 27 April 2015 at 19h31:42 at Kitwe in Zambia, arcing of a 220 kV isolator during switching operations led to tripping of a 240 MVA 330/220/11 kV transformer. This happened during a peak load. Kitwe and Luano are major substations carrying over half of the Zambian total system load. With the above event at Kitwe, the 240 MVA 330/220/11 kV transformer at Luano also tripped on overload. Subsequently, all the 330/220 kV transformers at Kitwe and Luano tripped. The disturbance quickly degenerated into a cascade of line, transformer and generator failures in Zambia (1650 MW) and Zimbabwe (1088 MW), resulting in major blackouts.

3) Tripping of Large Customer Load in South Africa: On 10 December 2015 at 00h02:44 during an off-peak hour, a large customer load of 445 MW tripped in Eskom, South Africa. The power system frequency rose to 50.38 Hz. Heavy inter-area power oscillations were observed until the interconnection between Eskom and ZESA tripped at 00h06:24. Then, the power system frequency on the Eskom island momentarily shot to 50.50 Hz. Data from PMUs (Phasor Measurement Units) confirmed that the triggered inter-area oscillations were at 0.3 Hz. Automatic action from generator governors plus running of pump storage units in pump mode assisted in arresting the frequency to normal band. See Fig. 7 below.

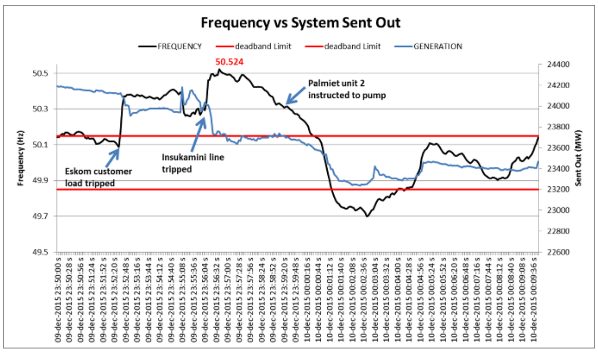

Fig. 7: Frequency and demand plots _ 10 December 2015

V. DISCUSSION

Prevalence of inter-area oscillations between south and north power systems in SAPP has been known ever since the synchronous operation was initiated. The NESATEAM study of 1997 identified an inter-area oscillatory frequency mode of 0.4 Hz [9]. Following another detailed study, the POD (power oscillation damper) on the SVC (static var converter) at ZESA's Insukamini border substation was re-tuned to damp the oscillations [14]. In 1212, a SAPP team carried out small signal stability studies and proposed updated settings for AVRs (Automatic Voltage Regulators) and PSSs (Power System Stabilisers) for units at key power stations in Zimbabwe, Zambia and Mozambique. As of year 2016, ZESA, ZESCO and HCB were in the process of validating the proposed settings and engaging original equipment manufacturers for implementation.

According to the NESATEAM, "the risk of undamped power oscillations must not limit the daily utilization of the network which should only be limited by the 'harder' limitations i.e. transient stability, voltage collapse, voltage drop or the thermal rating of lines" [9]. Therefore, while efforts to re-tune control systems are on-going, energy interchange is being scheduled as usual along SAPP interconnectors. Disturbances trigger power oscillations especially when the POD at Insukamini is out of service. In 2016 Eskom installed a PMU at Matimba Substation to facilitate monitoring and measurement of the oscillations. In the same year, ZESA implemented a special protection scheme at Insukamini. This scheme monitors oscillations and splits the interconnected system when the oscillations are un-damped for a prolonged duration. A comparison of typical system disturbances has shown that this scheme minimises impact of system disturbances and reduces restoration time.

In 2008, for the first time, major interconnectors between South Africa and Zimbabwe and between Zimbabwe and Zambia were left out of service for prolonged periods of time (several weeks) following major system disturbances. While running in isolated mode, two of the islands experienced blackouts on their own. It was learnt that interconnected operations enhance reliability. A joint technical team between ZESA and ZESCO investigated these disturbances. The team implemented the staggering of the operation of over-frequency protection among the generation units at Kariba North and Kariba South power stations. Instead of tripping at the same time, they were now differentiated in terms of magnitude of frequency, location of the unit, and time delay. It was also learnt that it is important to quickly come up with technical solutions to technical problems before politicians come up with unilateral directives.

Subsequently, a SAPP team, led by a consultant, also investigated the disturbances of 2008. Findings were: protection systems including automatic under-frequency load-shedding schemes performed well; damping of inter-area power oscillations was very poor; the risk of transient instability (loss of synchronism) following a fault was very high; transfer limits were not being adhered to; and, communication among Control Centres was poor. The team then made specific recommendations for improving damping of power oscillations, minimising the risks of transient instability, enhancing maintenance activities, and monitoring and reporting system disturbances. Investigation of the system disturbances was hampered by the fact that alarms and events data from the three control areas of SAPP were not timesynchronised. Phasor monitoring units would have really assisted in this regard.

In the new competitive electricity market environment, utilities are making every effort to optimise their generation and transmission resources for economic gains. The major blackouts of Italy and the U.S. in 2003 were mainly attributed to non-adherence to transfer limits, especially in the event of constraints. In SAPP, delays in despatching generation, errors in load forecasting, and poor operation of AGC (automatic generation control) systems are some of the factors which result in over-drawing power from neighbouring systems. Unfortunately, in some cases this led to tripping of transmission lines. as a mitigation measure, SAPP is enforcing operational discipline and has introduced penalties for non-compliance to operating guidelines.

When big loads trip in Zambia due to under-voltage, under-frequency or any other reason, the load is rejected southwards into Zimbabwe, leading to tripping of equipment. In 2016, ZESA implemented a special protection scheme at Kariba South. The scheme was designed to trip the interconnection instantaneously when the following criteria are satisfied: power of greater magnitude than 200 MW (a total of 400 MW on the interconnection) flows southwards from Zambia to Zimbabwe; and, the power system frequency is equal to or greater than 50.50 Hz. This scheme has assisted in minimising the impact of system disturbances characterised by load rejection from Zambia into Zimbabwe. Installation of capacitor banks, an SVC, and two more tie lines between Zambia and DR Congo has mitigated low voltage problems in the Copperbelt area.

Some disturbances were caused by vandalism of power equipment. In an effort to cab activities of vandalism, the SAPP formed a working group called Crime and Theft Prevention Working Group. The working group proposes inter-utility solutions that are channelled to law enforcing agents and policy makers. Involvement of local communities on security issues, branding materials, using vandal-proof designs, and replacing copper with aluminium conductors are some of the activities being promoted at regional level.

A great number of disturbances were characterised by power system frequency excursions following tripping of generators. Most utilities were not carrying the minimum required magnitude of operating reserves. With new generation, the SAPP is slowly moving out of a state of power supply deficit. In South Africa some customers are contracted to keep instantaneous reserves by automatically tripping specified amount of load when frequency dips to 49.65 Hz and below.

VI. CONCLUSION

New developments in the SAPP interconnected power system included commissioning of new equipment, changing physical configuration and embracing new operating state. These influenced the nature of system disturbances. This paper has presented the new developments in a period of over 15 years. The paper has also discussed system disturbances in relation to these new developments.

VII. RECOMMENDATION

Eminent new developments in SAPP include: 1) increased penetration of renewable energy sources; 2) increased distributed generation; and, 3) interconnection of SAPP with East Africa Power Pool (EAPP). These may bring new characteristics of system disturbances. As the interconnected power system grows, there is need to learn from historic trends of system disturbances. This may facilitate development of a resilient power system.

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APPENDIX 1: SAPP Interconnectors
Source: SAPP [1]